

AFRL-ML-TY-TR-2002-4511



**Cost and Performance Report
Use of Comatabolic Air Sparging to Remediate
Chloroethene-Contaminated Groundwater Aquifers**

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 1 August 2001		3. REPORT TYPE AND DATES COVERED Technical Report 26 Sep 99 to 18 Aug 00
4. TITLE AND SUBTITLE Cost and Performance Report – Use of Cometabolic Air Sparging to Remediate Chloroethene-Contaminated Groundwater Aquifers			5. FUNDING NUMBERS Contract No : F08637-95-D-6004 JON: 7305B58A PE: ESTCP	
6. AUTHORS Victor Magar				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Battelle Memorial Institute 505 King Avenus, Suite 5 Columbus, OH 43201-2693			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFRL/MLQL 139 Barnes Drive, Suite 2 Tyndall AFB, FL 32403-5323			10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-ML-TY-TR-2002-4511	
11. SUPPLEMENTARY NOTES Technical monitor: Capt David M. Kempisty, AFRL/MLQL, 850-283-6126 [DSN 523-6126]				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Distribution Unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (Maximum 200 words) The Environmental Security Technology Certification Program (ESTCP) supported an 18-month field study to investigate the cometabolic air sparging (CAS) process at the McClellan National Test Site, California. The purpose of the demonstration was to evaluate the effectiveness of and costs associated with CAS for removal of chlorinated aromatic hydrocarbons (CAHs) from groundwater. Specific project objectives were: <ul style="list-style-type: none"> • Evaluate subsurface oxygen and growth substrate (i.e. propane) distributions • Determine growth substrate acclimation requirements • Determine growth substrate and oxygen uptake rates, after acclimation • Evaluate the ability of indigenous bacteria to degrade different CAH compounds • Predict long-term process stability • Estimate CAS costs and compare costs with the cost of traditional air sparging or pump and treat technologies. This report describes the cost and performance aspects of the effort.				
14. SUBJECT TERMS CAH, chlorinated aromatic hydrocarbons CAS, Cometabolic Air Sparging			15. NUMBER OF PAGES 52	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

13. ABSTRACT (CONTINUED)

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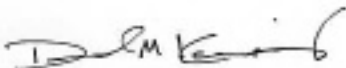
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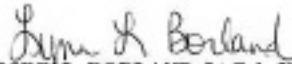
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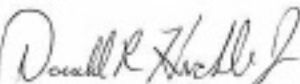
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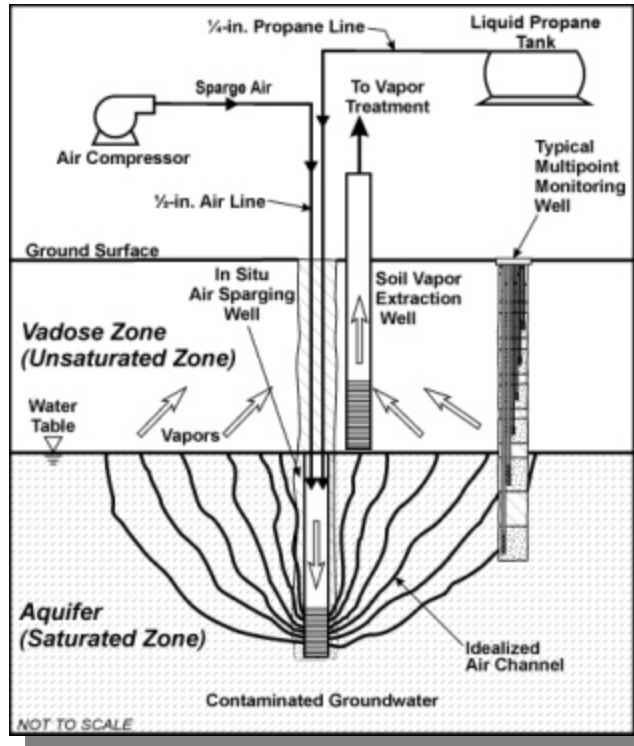


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Cost and Performance Report

Use of Cometabolic Air Sparging to Remediate Chloroethene-Contaminated Groundwater Aquifers



**Environment
al Security
Technology
Certification
Program**



August 2001

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ABBREVIATIONS AND ACRONYMS

AFB	Air Force Base
AFRL/MLQ	Air Expeditionary Forces Technology Division
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAH	chlorinated aliphatic hydrocarbon
CAS	cometabolic air sparging
CF	chloroform
CO ₂	carbon dioxide
DCA	dichloroethane
DCE	dichloroethylene
DO	dissolved oxygen
DoD	United States Department of Defense
DRE	destruction and removal efficiency
ESTCP	Environmental Security Technology Certification Program
FID	flame ionization detector
GAC	granular activated carbon
GC	gas chromatograph
GWMP	groundwater monitoring point
H ₂ SO ₄	sulfuric acid
HCl	hydrochloric acid
hp	horsepower
HP	Hewlett Packard
IAS	in situ air sparging
LFL	lower flammable limit
McAFB	McClellan Air Force Base
MCL	maximum contaminant level
MW	monitoring well
NA	not analyzed
NETTS	National Environmental Technologies Test Site (Program)
NH ₄	ammonia

NO ₃	nitrate
NRMRL	National Risk Management Research Laboratory
O ₂	oxygen
O&M	operation and maintenance
OSU	Oregon State University
OU	Operable Unit
P&T	pump and treat
PCE	tetrachloroethylene; perchloroethylene
PID	photoionization detector
ppmv	parts per million by volume
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
scfm	standard cubic feet per minute
SERDP	Strategic Environmental Research and Development Program
SF ₆	sulfur hexafluoride
SGMP	soil-gas monitoring point
slpm	standard liters per minute
SVE	soil vapor extraction
TCA	trichloroethane
TCE	trichloroethylene
TKN	total Kjeldahl nitrogen
USAF	United States Air Force
U.S. EPA	United States Environmental Protection Agency
VC	vinyl chloride
VOA	volatile organic analysis
VOC	volatile organic compound

ACKNOWLEDGEMENTS

This project could not have been completed without the extensive technical support and guidance from the Environmental Security Technology Certification Program (ESTCP), U.S. Air Force Research Laboratory (AFRL) (specifically Col. Tim Wiley, Lt. David Kempisty, and Paul Kerch), and McClellan Air Force Base (specifically Tim Chapman). Funding for this study was provided by ESTCP. In-kind funding was provided by McClellan AFB for the following items: construction of the sparge, SVE, and monitoring wells; fencing that surrounded the site; power and water; waste disposal for drill cuttings and liquid waste from sampling and on-site analysis; and technical support through report reviews.

1. Executive Summary

The United States Department of Defense (DoD) is faced with the task of remediating many sites contaminated with a variety of compounds, including chlorinated aromatic hydrocarbon (CAH) compounds. When a contaminant release occurs, these compounds may be present in the geologic media in any or all of three phases: adsorbed to soils, in free-phase form, or dissolved in groundwater. Of the three phases, dissolved contaminants in the groundwater are considered to be of greatest concern because of the risk of human exposure through drinking water; primary concerns for sorbed and free-phase contaminants often reside with their potential impact to groundwater. CAHs, used for years as industrial cleaners and degreasers, comprise some of the most common groundwater contaminants found at federal installations; chloroethenes and chloroethanes are among the most common solvents. The United States Air Force (USAF) uses more than 900 sites contaminated with chlorinated solvents in excess of drinking-water standards, and that may require cleanup. Industry, other government agencies, and up to 85% of Superfund sites (United States Environmental Protection Agency [U.S. EPA] and USAF, 1993) face similar cleanup situations.

The Environmental Security Technology Certification Program (ESTCP) supported an 18-month field study to investigate the cometabolic air sparging (CAS) process at McClellan Air Force Base, California. McClellan AFB (McAFB) was selected as the demonstration site for a variety of reasons: 1) McAFB has significant CAH groundwater contamination; 2) previous studies supported by the Air Expeditionary Forces Technologies Division (AFRL/MLQ), Tyndall AFB, Florida demonstrated that indigenous bacteria at McAFB could utilize propane as a growth substrate and support cometabolic CAH degradation; and 3) McAFB is a member of the Strategic Environmental Research and Development Plan (SERDP) National Environmental Technologies Test Site Program (NETTS) and expressed interest in this technology.

The purpose of this demonstration was to evaluate the effectiveness of and costs associated with CAS for removal of CAHs from groundwater. The demonstration will serve to disseminate new information about air sparging to assist DoD environmental managers with the task of evaluating remedial proposals for CAH contaminants. The following lists specific project objectives:

- Evaluate subsurface oxygen and growth substrate (i.e., propane) distributions
- Determine growth substrate acclimation requirements
- Determine growth substrate and oxygen uptake rates, after acclimation
- Evaluate the ability of indigenous bacteria to degrade different CAH compounds
- Predict long-term process stability
- Estimate CAS costs and compare costs with the cost of traditional air sparging or pump and treat (P&T) technologies.

The target CAH compounds for the CAS technology included a variety of chlorinated solvents, including trichloroethylene (TCE), dichloroethylene (DCE) isomers, vinyl chloride (VC), and trichloroethane (TCA) and lower chlorinated ethane isomers. The regulatory drivers for these environmental contaminants are maximum contaminant levels (MCLs) governed under the Safe Drinking Water Act (42 U.S.C. s/s 300f et seq., 1974).

As with traditional air sparging, CAS involves air injection directly into the aquifer. However, CAS is unique in that it also includes the addition into the aquifer of a gaseous organic growth substrate (growth substrate) to promote the in situ cometabolic degradation of CAH compounds. A CAS system is expected to be lower in cost and duration than a comparable P&T system. CAS costs also are expected to be lower than conventional air sparging, but the cost difference between CAS and air sparging is relatively small and may be site-specific.

The introduction of propane, methane, or butane gases with the sparged air stream introduces the potential for an on-site explosion. Safety considerations that were employed for this demonstration included 1) following all codes for propane use; 2) installing flash arrestors in all gas-transport lines; 3) sending the growth substrate gas and air to the saturated zone in separate lines, where they were mixed approximately 100 ft bgs in a 10-ft stainless steel sparge well; 4) pressure testing all propane (or methane) gas lines weekly to check for potential leaks; 5) using only hard pipe for propane lines; and 6) fencing the site to exclude unwelcome visitors. Other safety criteria may be required on a site-specific basis.

At the McAFB demonstration site, two test plots were used to test the efficacy of CAS. One test plot received propane and air, to stimulate cometabolic CAH degradation, and the other received air only, without propane, to monitor stripping and non-biological losses. CAS was shown to effectively treat groundwater contaminated with TCE and *c*-DCE and minor amounts of 1,1-DCE, 1,1-dichloroethane (1,1-DCA), and chloroform (CF). For detailed results, the reader is referred to the accompanying Final Report (Battelle 2001); this section summarizes the results of the Final Report.

CAS was applied to one sparge well in an active plot at the site, whereas air sparging only was applied to a parallel control plot without the addition of propane. Both plots had six multilevel groundwater and soil-gas monitoring points. Each multilevel well had two groundwater monitoring wells screened 113 and 117 ft below ground surface (bgs), and four soil-gas monitoring points screened at 30, 85, 95, and 105 ft bgs. The monitoring approach permitted detailed and careful monitoring of growth substrate degradation and CAH cometabolic degradation in the saturated and vadose zones.

In the saturated zone, CAH concentrations approached or fell below MCLs where they were maintained for long periods (more than 200 days) of continuous operation. In the active zone, CAH removal was closely attributed to propane degradation and cometabolism. However, CAH volatilization, observed in the control zone, also contributed to CAH removal. Volatilization occurred more slowly, and steady-state CAH concentrations were reached faster in the control zone than in the active zone.

Because CAH compounds volatilize into the vadose zone, vadose zone CAH degradation could contribute to the success of the CAS technology. At the McAFB site, for the >500 day operating period, propane degradation was not observed in the saturated zone, and no CAH cometabolism through propane degradation was observed. These results suggested that propane-degrading bacteria could not be stimulated for growth in the vadose zone under the operating conditions used for this demonstration. A possible nutrient limitation could have been nitrogen in the vadose zone; microcosm and field results showed that propane degradation slowed or stopped entirely when nitrogen in the form of nitrate was not present (Battelle, 2001).

Researchers at the U.S. EPA National Risk Management Research Laboratory (NRMRL), Cincinnati, OH, have effectively demonstrated the cometabolic bioventing process using propane as the cometabolic growth substrate, for vadose zone soils at Dover Air Force Base (AFB) (Sayles, 2000). At Dover AFB, propane uptake was rapid, and TCE concentrations were relatively low, typically only about 1 parts per million by volume (ppmv) with a few hits up to 20 ppmv. These reported results suggest that cometabolic CAH degradation using propane degraders also is possible, but that the ability to stimulate propane-degrading activity appears to be site-specific.

At the end of the McAFB study, methane was substituted for propane. Methane was rapidly degraded in the soil-gas monitoring points where it was detected. In two of the six deepest active-plot monitoring points, the first signs of propane degradation immediately followed methane degradation. The immediate degradation of propane to non-detectable levels following methane degradation came as a surprise, and suggested that either methane stimulated the direct degradation of propane or that propane was degraded cometabolically by the growth of methanotrophs in the vadose zone.

TCE concentrations in soil gas point SG-C1-95 (95 ft bgs) remained very stable, while *c*-DCE concentrations showed decreasing concentrations between Days 510 and 590, after methane was introduced into the aquifer. Much more significant decreases in both TCE and *c*-DCE concentrations were observed in soil-gas monitoring point SG-C3-95 (95 ft bgs), in which concentrations were below detection limits for both compounds by the time of the last sampling event (Day 590). SG-C3-95 was the only soil-gas monitoring point that showed complete CAH removal with the introduction of methane into the sparge gas.

The fact that propane and CAHs disappeared in SG-C3-95 strongly suggests that the CAHs were degraded cometabolically by methanotrophs (or propane-degrading bacteria if propane was not cometabolically degraded) in the vicinity of this soil-gas monitoring point. It is possible that clean soil gas migrated into the area, thereby displacing the CAHs in the vadose zone near SG-C3-95; however, the stable concentrations monitored in virtually all the deep soil-gas monitoring points for over 500 days suggests that the CAHs did not disappear through displacement alone, and that biodegradation likely played a major role in their disappearance. Limited time did not permit confirmation of these results, nor did it permit the continued methane addition and monitoring to promote CAH cometabolism near the other soil-gas monitoring points. Thus, it

was not possible to confirm whether CAH cometabolism would have ensued after repeated methane addition.

These results suggest that cometabolic CAH degradation in the saturated and vadose zones could be achieved, although multiple growth substrates may be required for different treatment zones.

2. Technology Description

2.1 Technology Development and Application

Air sparging is the process of injecting clean air directly into an aquifer for remediation of contaminated groundwater. In situ air sparging (IAS) is used to remediate groundwater through a combination of volatilization and enhanced biodegradation of contaminants. The induced air transport through the groundwater removes the more volatile and less soluble contaminants by physical stripping, and increased oxygen availability in the groundwater stimulates increased biological activity. Soil vapor extraction (SVE) may be combined with air sparging to control vapors emitted during the sparging process, particularly for CAH-contaminated sites.

CAS is an innovative form of conventional air sparging designed to remediate CAH-contaminated groundwater and to reduce off-gas CAH emissions. As with traditional air sparging, CAS also involves air injection directly into the aquifer. However, CAS is unique in that it also includes the addition into the aquifer of a gaseous organic growth substrate (growth substrate) to promote the in situ cometabolic degradation of CAH compounds.

2.1.1 Technology Background, Development, Function, and Intended Use. CAS was developed as an extension of conventional air sparging to remediate groundwater contaminated with chlorinated solvents that are otherwise recalcitrant to aerobic degradation. Numerous studies have shown that various chlorinated solvents can be degraded cometabolically under aerobic conditions, by propane-, butane-, or methane-degrading bacteria. The CAS concept combined the knowledge of cometabolic degradation using bacteria that grow on these gaseous substrates with the more conventional air sparging approach.

2.1.2 Systems to Which the Technology is Applicable. The CAS technology is applicable to sites where groundwater is contaminated with chlorinated solvents that are known to be degraded cometabolically using butane, propane, or methane as primary growth substrates. The technology is limited to sites where air sparging would otherwise be considered an acceptable approach, but whose contaminants cannot be degraded as primary growth substrates and can only be degraded cometabolically. Target contaminants would include lower chlorinated ethenes (TCE, DCE isomers, and VC) and lower chlorinated ethanes (TCA and DCA isomers). The technology is not applicable to sites contaminated with compounds that are recalcitrant to aerobic cometabolism, such as perchloroethylene (PCE) and carbon tetrachloride.

2.1.3 Target Contaminant(s). Target contaminants are identified in included lower chlorinated ethenes (TCE, DCE isomers, and VC) and lower chlorinated ethanes (TCA and DCA isomers). Please refer to Section 2.2.4, which discusses Regulatory Drivers.

2.1.4 Theory of Operation. CAS removes contaminants from saturated soil sediments through three primary removal mechanisms:

1. Increased dissolved oxygen (DO) plus propane introduction supports propane degradation; growth of indigenous propane-degrading bacteria results in the subsequent cometabolic degradation of CAHs.
2. Increased DO enhances in situ biodegradation by indigenous microbes of contaminants that can be used as substrates for energy and growth.
3. Volatile organic compounds (VOCs) partition into the vapor phase and are transported to the vadose zone in the air stream where they may be degraded cometabolically, captured by an SVE system, or released to the atmosphere, depending on the system design, the contaminant, and regulatory requirements. Significant VOC degradation in the vadose zone may occur for VOCs that can oxidized aerobically, such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Cometabolic degradation of VOCs also may occur if sufficient growth substrate is present in the vadose zone to support cometabolism, and if the growth substrate itself degrades in the vadose zone.

The relative contribution of each of these removal mechanisms is dependent on site characteristics, contaminant type and concentration, system design, and operational parameters.

2.2 Process Description

Conceptually, CAS is a simple process of injecting a gaseous substrate such as propane with air beneath a groundwater table. Like conventional air sparging, CAS uses conventional installation techniques and common equipment such as air compressors, piping, and wells. The major components of a typical cometabolic air sparging system are shown in Figure 1, including an air injection well, an air compressor or blower to supply air, monitoring points and wells, and an optional SVE system.

A detailed description of the specific system design used at McAFB can be found in the Final Report for this study (Battelle, 2001).

2.2.1 Mobilization, Installation, and Operational Requirements. Conceptually, CAS is a simple process of injecting a gaseous substrate such as propane with air beneath a groundwater table. Like conventional air sparging, CAS uses conventional installation techniques and familiar equipment such as air compressors, piping, and wells. The major components of a typical cometabolic air sparging system are shown in Figure 1, including an air injection well, an air compressor or blower to supply air, monitoring points and wells, and an optional vapor extraction system.

The air injection wells generally are vertical and are screened at depths located below the contamination level. The wells are grouted to depths below the water table to prevent short-circuiting of air through a sand pack into the vadose zone. If the medium is homogenous sand, the airflow will be relatively uniform around the air injection well, resulting in good mass transfer. In contrast, a heterogeneous medium may result in nonuniform and confining airflow

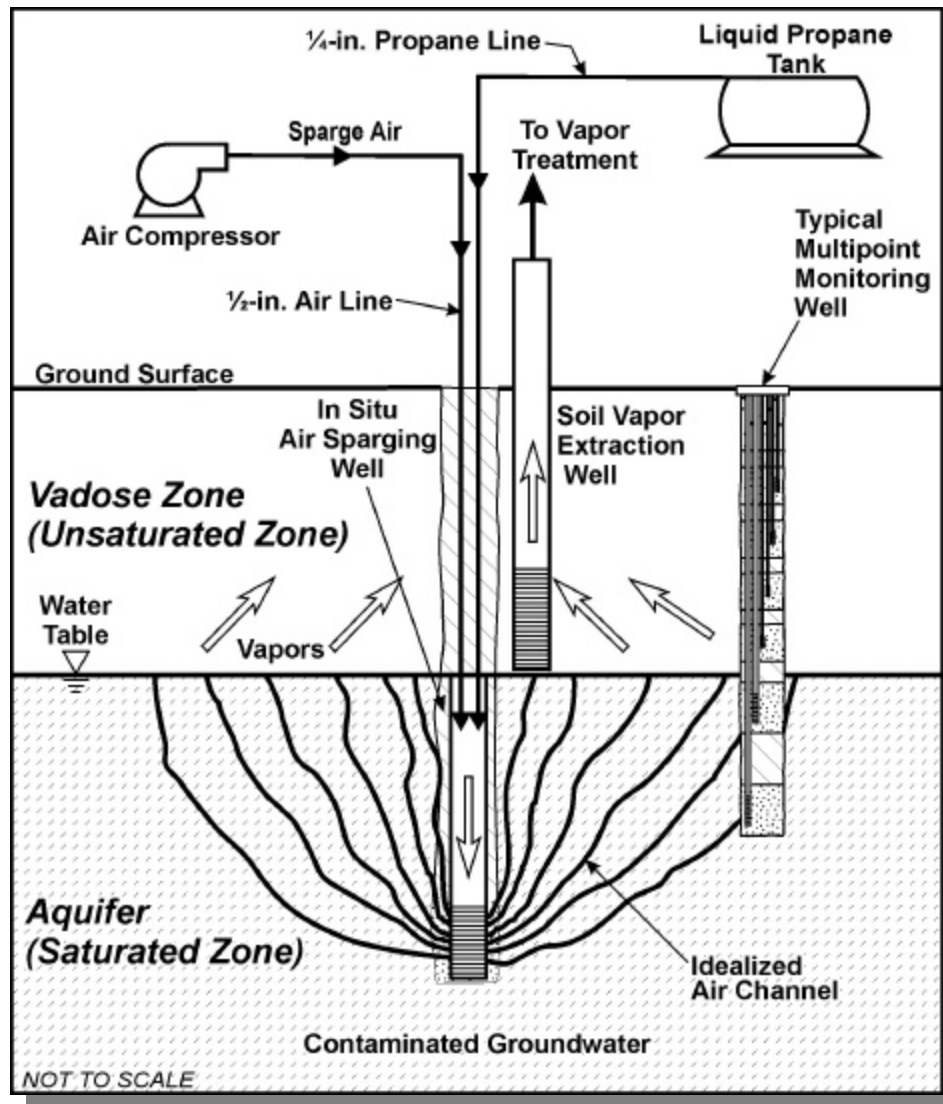


Figure 1. Conceptual Cometabolic Air Sparging Process Diagram

thus reducing air sparging effectiveness. In practice, all sites have some degree of soil heterogeneity and nonuniform airflow is common. The practitioner must ensure that the nonuniformity of airflow is acknowledged and accounted for in the system design.

Compressors or blowers are needed to supply air to the injection wells. The selection of a compressor or blower depends upon site-specific characteristics that dictate airflow and pressure requirements. The monitoring points and related equipment are needed to provide information on compressor airflow rates and pressure, and contaminant concentrations in the groundwater, soil, and effluent air stream to analyze the progress of the remediation. In some air sparging systems, an optional vapor extraction well is installed to transfer contaminated vapor from the

vadose zone for treatment. Blowers require approximately 30% less energy than compressors and result in approximately 50% less noise. However, blowers have much less capacity than compressors to overcome strong hydrostatic pressures. Consequently, compressors are more suited to greater depths and tighter formations than blowers.

One major difference between air sparging and CAS systems, besides the addition of a gaseous growth substrate to the sparge gas, is the enhanced design to promote safety and to reduce the risk of explosive hazards. The introduction of propane, methane, or butane gases with the sparged air stream introduces the potential for an on-site explosion. Safety considerations that were employed for this demonstration included 1) following all codes for propane use; 2) installing flash arrestors in all gas-transport lines; 3) sending the growth substrate gas and air to the saturated zone in separate lines, where they were mixed approximately 100 ft bgs in a 10-ft stainless steel sparge well; 4) pressure-testing all propane (or methane) gas lines weekly to check for potential leaks; 5) using only hard pipe for propane lines; and 6) fencing the site to exclude unwelcome visitors. Other safety criteria may be required on a site-specific basis.

2.2.2 Key Design Criteria. Key design criteria include well spacing, injection rates, propane consumption, monitoring requirements, equipment sizing, and treatment duration. The criteria below are described for a system utilizing propane as the carbon source and should be adjusted accordingly if either butane or methane gas is used as the primary growth substrate.

- Well spacing should be based on the Air Sparging Design Paradigm (Leeson et al., 2000).
- Injection rates, injection frequency, and propane requirements should be based on site-specific pilot studies and will depend on the rate of biological propane consumption. Unlike conventional air sparging, the primary goal of CAS is not to strip contaminants to the vadose zone; rather, it is to promote propane and contaminant degradation in the saturated zone.
 - Injection rates should be as low as possible, while maintaining a reasonable zone of influence. Typical air sparging injection rates range from 5 to 20 standard cubic feet per minute (scfm). Air injection rates for cometabolic air sparging should be at the lower end of this range to minimize contaminant volatilization.
 - Sparging with propane should be conducted intermittently to allow depletion of propane in groundwater between sparge events.
 - Propane should be added at a concentration of 1 to 4% in the injection air, depending on propane utilization rates. The stoichiometric equivalent propane concentration to 20% oxygen in air is 4%. Thus, 4% is the maximum proposed propane concentration to prevent anaerobic conditions. Lower concentrations (1% to 2%) are recommended to

minimize microbial competition between propane and the contaminant of interest.

- Post-treatment monitoring is required to assess the potential for contaminant rebound.
- Equipment such as air compressors, flow meters, and pressure gauges should be sized according to site-specific sparge requirements.
- Monitoring should be conducted biweekly to monthly for the first six months to verify in situ degradation of the primary growth substrate and cometabolic CAH degradation. Thereafter, monitoring may be conducted on a much less frequent basis to verify the biologically active system.

2.2.3 Performance. Technology performance is based on achievement of site-specific cleanup goals in groundwater. In the case of this study, the performance goal was to achieve MCLs for groundwater contaminants.

2.2.4 Target Regulatory Standards to be Met for Cleanup and Site Characterization. The target CAH compounds for the CAS technology include a variety of chlorinated solvents, including TCE, DCE isomers, VC, and TCA and lower chlorinated ethane isomers. The regulatory drivers for these environmental contaminants are MCLs (Table 1), governed under the Safe Drinking Water Act (42 U.S.C. s/s 300f et seq., 1974).

Table 1. Regulatory Drivers for CAS Target Contaminants

Organic Chemical	MCL (mg/L)	Potential Health Effects from Ingestion of Water
Tetrachloroethene	0.005	Liver problems; increased risk of cancer
Trichloroethene	0.005	Liver problems; increased risk of cancer
1,1-Dichloroethene	0.007	Liver problems
<i>cis</i> -1,2-Dichloroethene	0.07	Liver problems
<i>trans</i> -1,2-Dichloroethene	0.1	Liver problems
Vinyl chloride	0.002	Increased risk of cancer
1,1,1-Trichloroethane	0.2	Liver, nervous system, or circulatory problems
1,1,2-Trichloroethane	0.005	Liver, kidney, or immune system problems
1,2-Dichloroethane	0.005	Increased risk of cancer

Source: <http://www.epa.gov/safewater/mcl.html#3> (accessed December 2000).

2.2.5 Personnel/Training Requirements. Tasks associated with long-term operation of a CAS system are relatively simple and require minimal operator experience. A field technician capable of performing weekly systems checks to verify flowrates and proper operation of the system compressor is sufficient. Maintaining the desired air:propane ratio throughout the operation was conducted routinely. Compressors will require periodic maintenance, but generally can be operated for several years before replacement is necessary.

2.2.6 Health and Safety Requirements. Health and safety requirements are stringent when applied to cometabolic air sparging compared to just air sparging. Propane installation and on-site storage need to follow local, state, and federal regulations. These requirements could include placing the propane tank on a concrete pad, installing collision posts along the perimeter of the pad, using hard line above ground piping materials, and enclosing the propane tank and piping in a fence. The system should not be installed near any building or areas of heavy pedestrian or automobile traffic so the potential of the injected air:propane mixture migrating into nearby building or underground utilities is limited. The propane/air sparge well should be buried beneath the soil to reduce the chance of an explosive event. A hydrocarbon analyzer should also be installed to continually monitor the system when the air with the propane mixture is being injected. The analyzer should be connected to a shutdown switch, so if the air compressor fails the propane will shut off.

2.2.7 Ease of Operation. In general, the ease of use of the CAS technology is comparable to that of conventional air sparging. However, as indicated in Section 2.2.6, special precautions must be made when working with an explosive gas such as propane, butane, or methane. Monitoring the CAS technology is generally similar to that of conventional air sparging. However, CAS requires technical knowledge of biological processes that are expected to occur, including degradation of the primary growth substrate, oxygen utilization during substrate degradation, and cometabolic degradation reactions.

2.3 Previous Testing of the Technology

Researchers at U.S. EPA NRMRL, Cincinnati, OH, effectively demonstrated the cometabolic bioventing process using propane as the cometabolic growth substrate, for vadose zone soils at Dover AFB (Sayles, 2000). At Dover AFB, propane uptake was rapid, and TCE concentrations were relatively low, typically about 1 ppmv with a few samples up to 20 ppmv.

When conducting a similar study at Hill AFB, the same researchers were unable to stimulate propane degradation and cometabolic CAH degradation in the vadose zone, despite successful microcosm studies that demonstrated propane degradation using the Hill AFB soils (Sayles, 2000). One significant difference between Dover AFB and Hill AFB conditions was the CAH concentration at each base. Concentrations at Hill AFB were around 1000 ppmv. Using Henry's law, 1000 ppmv would equate to approximately 300 mg/L (solubility is approximately 1,100 mg/L). Dr. Sayles and his coworkers speculate that their inability to stimulate propane degradation at Hill AFB is attributed to the high TCE concentrations in the vadose zone, resulting in high aqueous phase concentrations in the vadose zone porewater and potentially toxic conditions for propane-degrading bacteria.

2.4 Advantages and Limitations of the Technology

CAS has several advantages over conventional remediation technologies, combining the benefits of conventional air sparging with the added value of cometabolic activity. Specific advantages are described in the following paragraphs.

- Air sparging is an aggressive process that can remove contaminants at a much faster rate than can standard pump-and-treat systems.
- The cometabolic component of CAS allows for enhanced biodegradation of CAHs in groundwater to accelerate their removal, reduce vapor emissions, and increase the degree of remediation attainable. This component of CAS also results in mineralization of the CAHs, which may be preferable to transfer of the contaminants to another matrix.
- CAS is a simple process that uses commercial, off-the-shelf equipment.

Disadvantages of CAS do exist and require thorough evaluation prior to implementation of the technology. Some uncertainties about long-term effectiveness will remain, as is the case with any innovative technology, but proper monitoring and evaluation can mitigate these uncertainties. Specific disadvantages include the following:

- Similar to most remedial technologies, the effectiveness of air sparging can be limited by soil heterogeneities at a site (i.e., differing permeabilities). Nonuniform distribution may lead to areas that are not treated directly.
- At very large or very deep sites, air sparging costs may become prohibitive as a result of the relatively small zone of influence of the injected air.
- CAS relies on the degradation of the primary growth substrate and cometabolic CAH transformation in the saturated zone and in the vadose zone for volatilized contaminants. Thus, microorganisms that can catalyze these reactions must be present in both the saturated and vadose zones.
- If bacteria are not available, bioaugmentation may be a necessary step. However, to date there are no reports of in situ bioaugmentation for cometabolic degradation of environmental contaminants, making this an untested approach.
- CAS relies on cometabolic CAH degradation in both the saturated and vadose zones. In some cases, CAH cometabolism in the vadose zone may play a larger role than degradation in the saturated zone, and may be critical to the efficacy of CAS, due to the ease of CAH stripping from the saturated zone.

CAS is a new and innovative technology that uses air sparging principles but attempts to optimize in situ contaminant degradation by adding a growth substrate to the vapor stream. Because CAS is in a relatively young stage of development, the effectiveness of growth substrate addition and its potential to result in cost savings by reducing aboveground vapor treatment were subjects of this study.

3. Demonstration Design

3.1 Performance Objectives

The primary performance objective for this study was to conduct cometabolic air sparging at McAFB. The goal was not to remediate the site below regulatory levels, but rather to determine whether CAS is effective and whether employed monitoring techniques adequately predict performance. Other specific objectives included the following:

- Comparing air sparging effectiveness with and without the propane growth substrate, using one control and one propane-fed sparge well
- Monitoring propane degradation rates
- Establishing the effective zone of influence for oxygen and propane
- Establishing CAH concentration reductions resulting from CAS, and the relative contributions to site remediation of CAH stripping and cometabolic CAH degradation
- Conducting an economic analysis of cost and performance of CAS.

3.2 Selection of Test Site

The McAFB site has relatively high TCE concentrations and a wide distribution of CAH compounds. This study was conducted at Operable Unit A (OU A). Upon first inspection, OU A appeared to have relatively permeable zones and to be geologically suitable for air sparging. However, drilling at the site revealed a heterogeneous aquifer with some relatively low permeable zones where sparging was hindered. The site also was remotely located at the southern end of the base in an area of low vehicular traffic and minimal aboveground obstructions.

Oregon State University preformed microcosm studies with soil collected from OU A before installation of the system. The results showed that propane-degrading bacteria were present in the saturated zone of the site, indicating that propane would be a suitable primary growth substrate to promote in situ CAH cometabolism.

3.3 Test Site/Facility History/Characteristics

McAFB is located approximately 7 miles north of Sacramento, California. In July 1987, the base was placed on the U.S. EPA's National Priorities List. In 1993, McAFB was designated a SERDP National Test Site. McAFB is divided into 11 operable units, designated as OUs A through H, OU B1, OU monitoring well (MW) C1 (MW-C1), and OU GW. The CAS demonstration was conducted at OU A. The TCE plume in this area is shown in Figure 2. The site has TCE concentrations in excess of 500 µg/L.

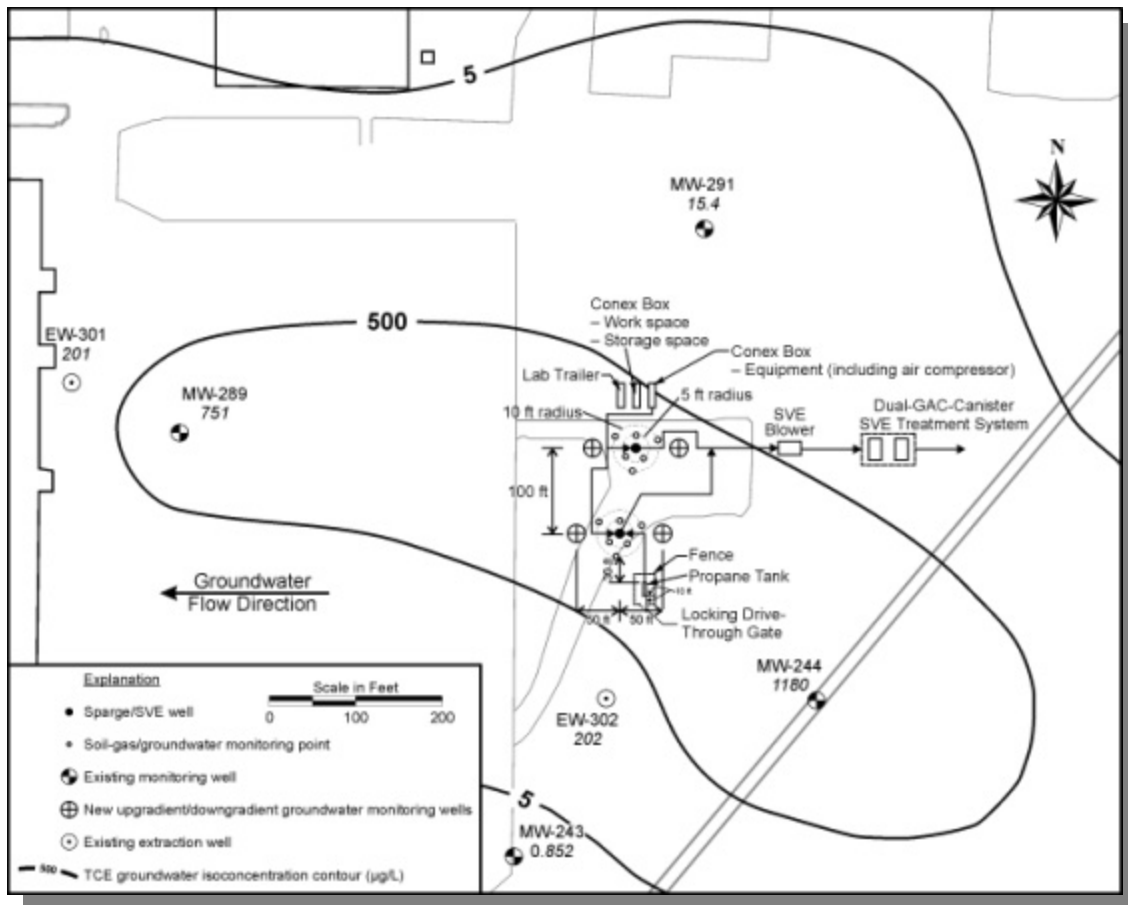


Figure 2. TCE Plume Contours and Demonstration Layout at OU A

OU A is the location of a former demolition and scrap material burning and burial pit that was operational from 1964 to 1969. Materials that were burned or buried include residues, scrap material, fuels and oils, solvents, semivolatile organic compounds, and volatile organic compounds. Around 1969, the activities ceased and the pit was filled. From 1953 to 1964, the site was used to store miscellaneous materials. Before 1953, the site was undeveloped grassland.

3.4 Physical Set-Up and Operation

3.4.1 Construction Details. The treatment process included sparge wells, SVE wells, multi-level soil and groundwater monitoring points, an air injection system, an SVE blower, propane gas storage and injection system, and an on-site field trailer (Figure 3).

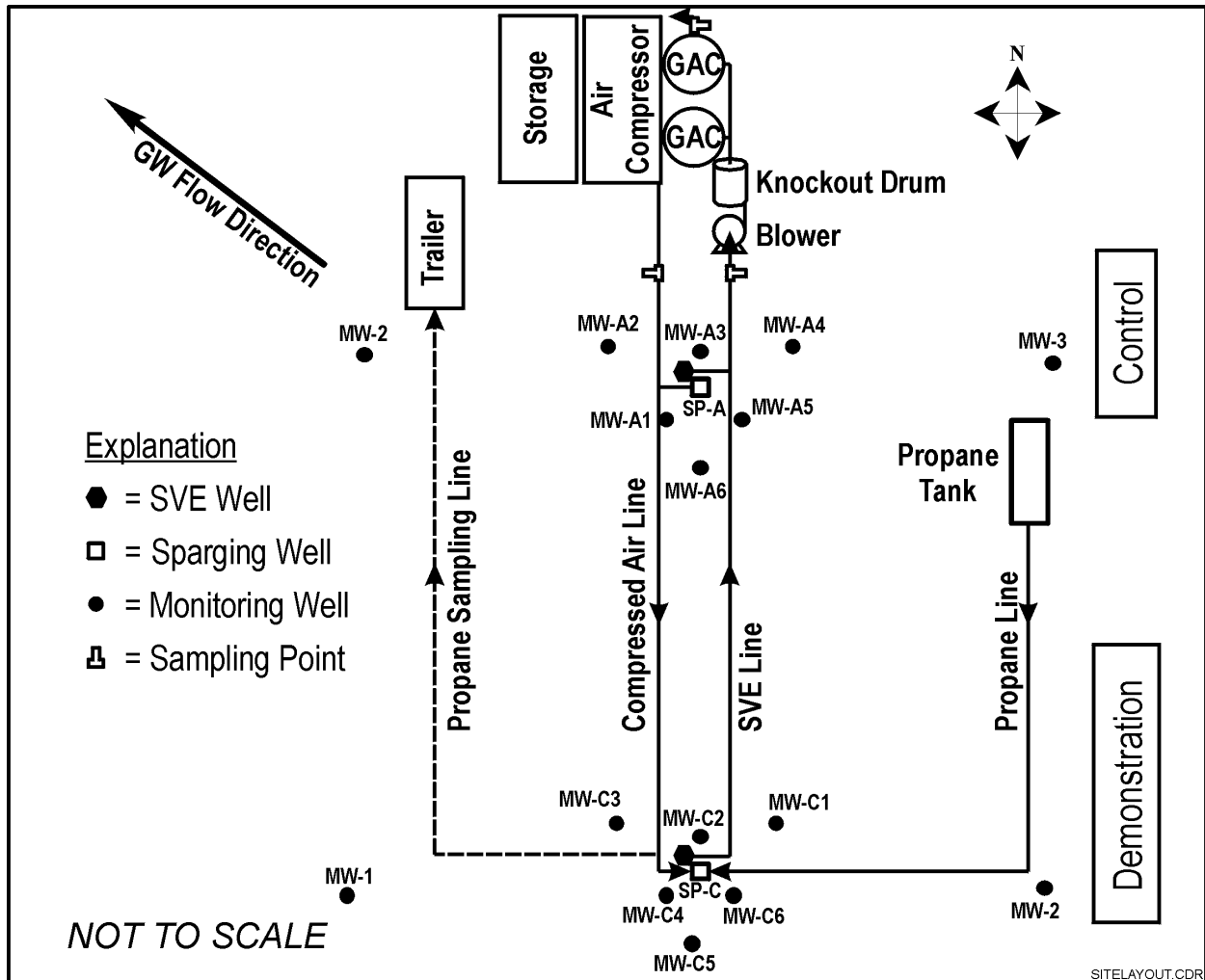


Figure 3. CAS Site Layout at McClellan AFB

McAFB installed all wells. A Battelle staff member was on site to provide technical input and supervision. McAFB initiated dig and well permits, selected a drilling contractor, and scheduled the drilling.

Two test plots were created; was used to test the CAS process and one served as a control. One sparge well was installed in each test plot. The sparge wells were located 100 ft apart. The control sparge well received air only (sparge well SP-A located in the control test plot), and the test sparge well received propane plus air (sparge well SP-C located in the active test plot). Construction details were the same for both sparge wells to ensure similar performance during operation and to increase flexibility for future experiments. Sparge well construction and installation details are provided in the Final Report (Battelle, 2001); sparge well construction details are shown in Figure 4.

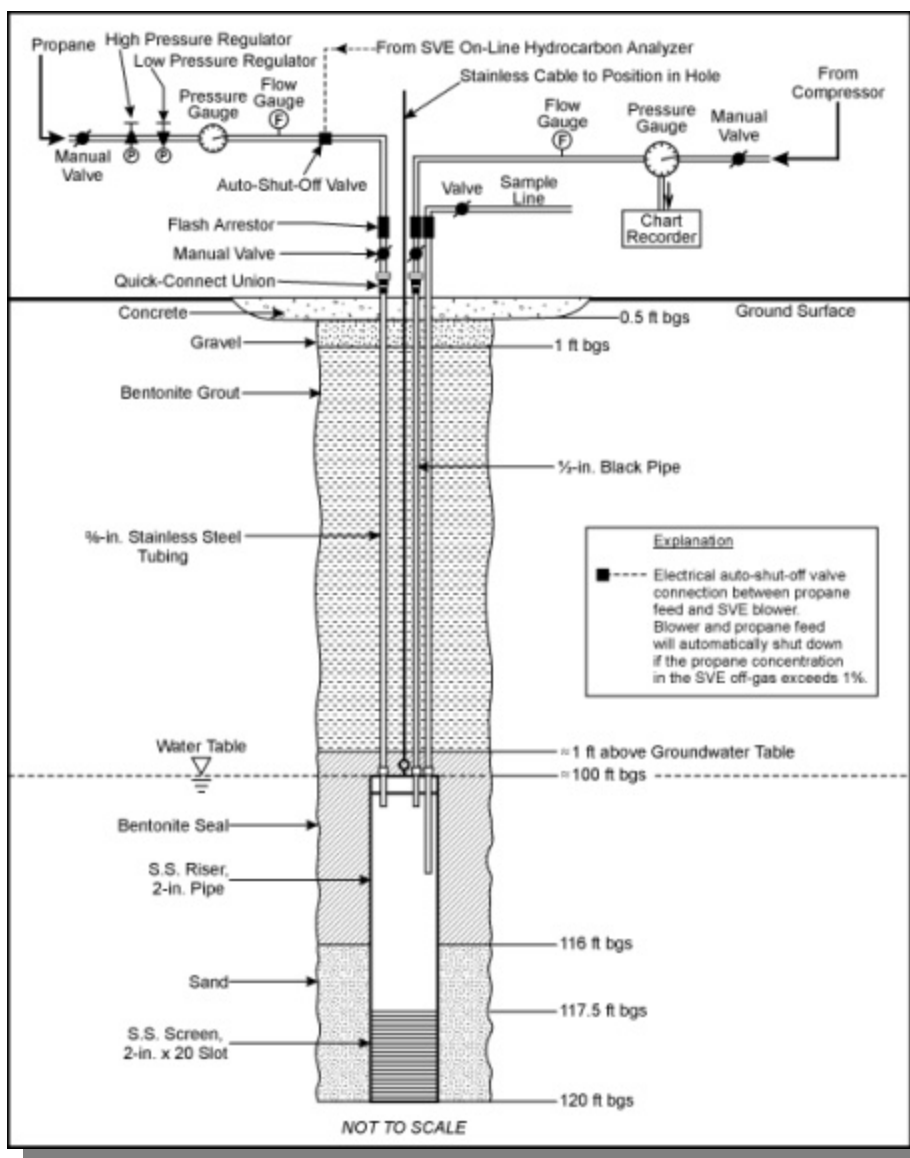


Figure 4. As-Built Sparge Well Configuration

3.4.2 Soil Vapor Extraction Wells. A single SVE well was constructed adjacent to and as close as possible to each sparge well. The SVE wells were screened from 90 ft bgs to the lowest recorded water table depth, approximately 100 ft bgs, using 20-slot, 2-inch-diameter, Schedule 40 polyvinyl chloride (PVC). The casing extended from the ground surface to 90 ft bgs, and consisted of 2-inch-diameter Schedule 40 PVC pipe. The SVE wells were used as a safety precaution in the event that the above ground vapor CAH concentrations exceeded McAFB requirements. This did not occur throughout the demonstration, and the SVE system was not used. The SVE wells were manifolded to a feeder pipe that conducted the vapor through an extraction blower, a detachable water knockout vessel, and granular activated carbon (GAC)

canisters for treatment prior to discharge, to meet McAFB's 95% destruction and removal efficiency (DRE) requirement for extracted vapors. SVE construction details are provided in the Final Report (Battelle, 2001).

3.4.3 Groundwater and Soil-Gas Multi-Level Monitoring Points. Six monitoring points were installed surrounding each sparge well in a manner that allowed for the collection of soil gas and groundwater from a single sampling location at discrete depths (Figure 5). The soil-gas monitoring points were used to monitor soil-gas concentrations of carbon dioxide, oxygen, propane, and CAHs. The groundwater monitoring points were used to collect groundwater samples for DO, propane, and CAHs. The multilevel monitoring points consisted of two groundwater monitoring points screened at 113 and 117 ft bgs (bottom of screens), and four soil-gas monitoring points screened at 30, 85, 95, and 105 ft bgs. Monitoring points in the vadose zone consisted of 1/4-inch-diameter nylon tubing to their specified depths. Groundwater monitoring points consisted of 2-inch-diameter PVC pipe, with 10-slot, 1.0-ft-long screens. The upper groundwater monitoring points were screened from 112 to 113 ft bgs, while the lower groundwater monitoring points were screened from 116 to 117 ft bgs. Construction details are provided in the Final Report (Battelle, 2001).

The following nomenclature was used to identify the monitoring assembly. Monitoring points in the control test plot were labeled A and those in the active test plot were labeled C. The groundwater monitoring locations are represented by their depth 113 ft and 117 ft bgs, respectively (i.e., groundwater monitoring points at the 113 ft bgs level were labeled as MW-A1-113 through MW-A6-113 and MW-C1-113 through MW-C6-113).

Soil gas points were labeled according to their depth in the vadose zone; they were installed at 30-, 85-, 95-, and 105-ft bgs, respectively. For example, soil-gas points at the well C1 are labeled as SG-C1-30, -85, -95, or -105, depending on the depth of the soil-gas point.

3.4.4 Air Injection System. The air compressor supplied airflow and pressure to produce 25 pounds per square inch (psi) delivery air pressure and 15 scfm (maximum) airflow rate to each sparge well. A Quincy QRDS-15T120, 15-horsepower (hp), 208V three-phase, oilless air compressor was selected to provide durable, low-maintenance, and continuous heavy-duty air delivery for the project duration. For safety purposes, the compressor was located a minimum of 50 ft from the propane storage tank and propane gas lines, which is twice the required distance of 25 ft.

A 6-hp, multispeed blower, capable of operation at two to three speeds, was used for vapor extraction from the SVE wells. For safety, the blower was built with explosion-proof electrical (i.e., Class 1, Div 1) and mechanical components. Installing an ambient air bypass valve that could dilute the SVE off-gas with ambient air provided additional safety. The SVE system was designed to extract 45 scfm per well, 3 times the maximum injection rate of 15 scfm. The system was constructed so that propane injection would stop if the air blower failed (this never occurred).

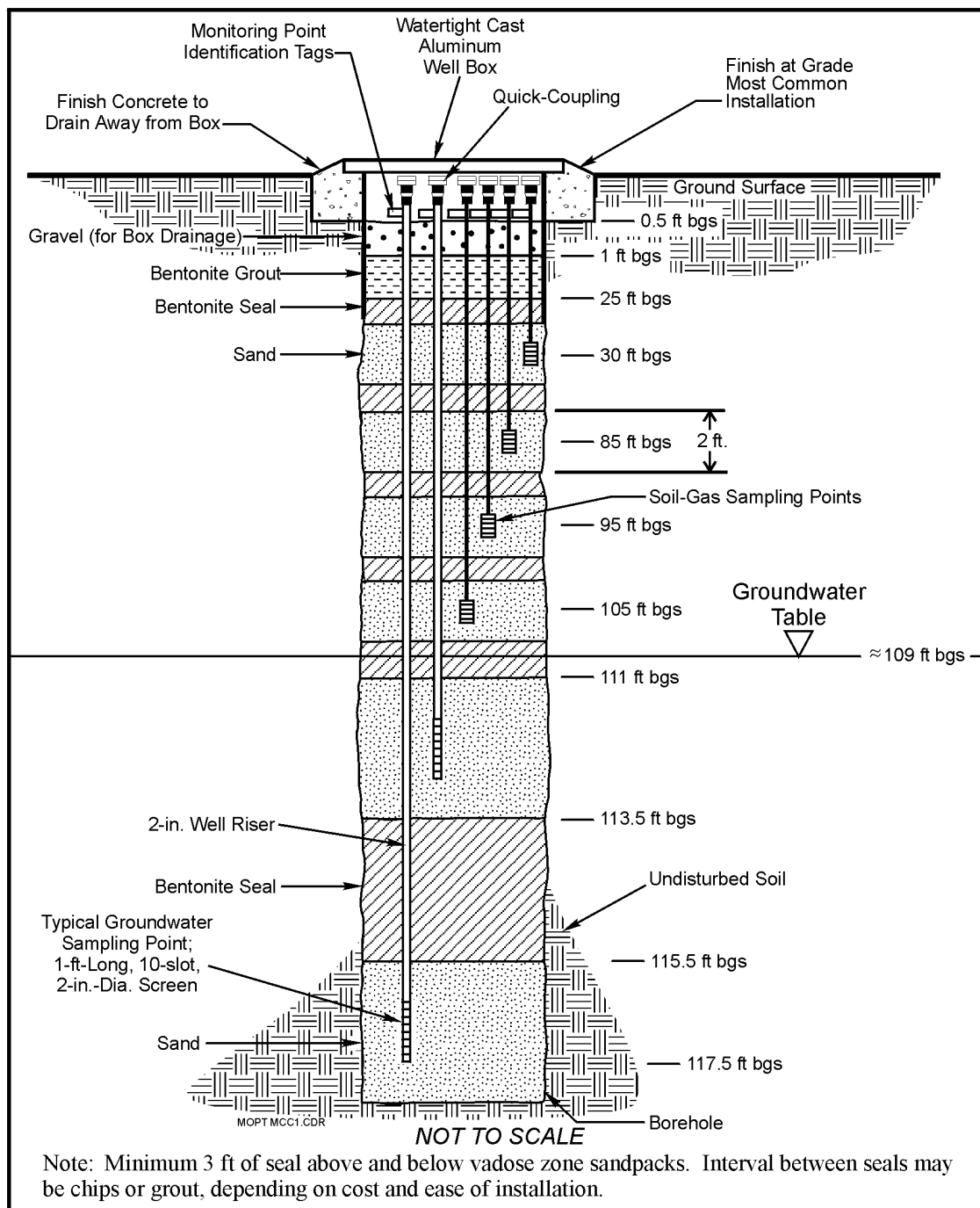


Figure 5. As-Built Layout for Multi-level Soil Gas and Groundwater Monitoring Points

3.4.5 Propane Gas Storage and Injection System. Propane gas was supplied by a certified provider (Kamps, Manteca, CA), and stored on site in a 1,000-gallon tank. The propane injection system was constructed with in-line propane sensors and shutdown switches that would shut the system down if propane concentrations in the SVE lines reached 50% of the lower flammable level (LFL) (i.e., 1%), or if the air injection or vapor extraction systems failed. All sensors and alarms were explosion proof, as required, if they were likely to come into contact with propane.

The demonstration was conducted using 95% grade propane, which was a higher grade than commercial propane (generally 80 to 90% propane). Special measures were taken to make the propane odor-free, because of concern that the methyl mercaptain compounds added to commercial propane mixtures for odor could be harmful to the propane-degrading bacteria. The use of odor-free propane created other risks, particularly a risk of an unknown leak that would not be detected by smell. For this reason, all propane gas lines were monitored for leaks on a weekly basis. This resulted in increased monitoring costs. Costs also were impacted slightly by requiring a more expensive grade of propane than commercial grade.

The propane was injected into sparge well SP-C via a separate gas injection line. The propane was mixed with air in the sparge well at a depth of approximately 115 ft bgs. The maximum atmospheric concentration of propane introduced with air into the sparge well was approximately 4%, to provide a 5:1 oxygen:propane ratio. This ratio is calculated from the stoichiometry of propane and oxygen consumption shown in Equation 1:



The 4% propane concentration was the *maximum* target concentration of growth substrate that was employed during CAH testing. However, generally propane was added at lower concentrations, ranging from 1 to 4%.

Safety precautions undertaken for the propane feed system are described in the Final Report (Battelle, 2001).

3.4.6 Field Analytical Trailer. An Air Force field analytical trailer provided workspace for data analysis and other field tasks. The trailer belongs to AFRL/MLQ. The field gas chromatograph (GC), test kits, reagents, and analytical gases for the field demonstration were housed within the existing AFRL/MLQ laboratory trailer for the duration of the field demonstration. The trailer was equipped with a Hewlett Packard (HP) GC, Model 5890, with a flame ionization detector (FID) and photoionization detector (PID), and a purge-and-trap sampler with 16 auto sample ports. The GC was set up, calibrated, and operated by Battelle. The GC was fitted with a GSQ-PLOT column (J&W Scientific, Folsom, CA).

3.5 Sampling/Monitoring Procedures

Preliminary system testing was conducted prior to initiation of propane injection. The exception is the sulfur hexafluoride (SF₆) tracer test that was conducted during Phase 2. The following activities were conducted as part of the system testing:

- Equipment shakedown
- Baseline testing
- Helium tracer testing
- Pressure transducer testing
- SF₆ tracer testing.

For a detailed discussion of the preliminary testing activities and their results, the reader is referred to the Final Report (Battelle, 2001). A schedule of operation is shown in Table 2.

3.5.1 System Operation. The CAS field demonstration was conducted for 540 days at McAFB and was divided into two phases. Phase 1 focused on the groundwater remediation and propane degradation along with CAH dechlorination. Phase 2 of the demonstration focused on propane degradation and CAH remediation in the unsaturated zone. Table 2 shows the schedule for Phases 1 and 2, the number of days of operation for each phase, and startup periods for each phase.

To minimize stripping and maximize biodegradation, particularly during startup, sparging was conducted intermittently. Intermittent sparging involved sparging for 4 hours to saturate the formation with propane and oxygen, and turning off the sparge well for a predetermined period (generally one week). The length of time between intermittent sparging depended on the rate of groundwater flow and the rate of propane degradation. This was determined by monitoring of groundwater for DO and propane. The control well (without propane) was operated under the same conditions as the propane-fed well for comparison between the wells.

The site was staffed 75% to 100% of the time during system operation. The on-site staff checked the mechanical equipment daily (Monday through Friday), including blowers, compressors, flow meters, and pressure meters, according to manufacturer requirements. Airflow meters, pressure gauges, and other monitoring equipment were adjusted when used and recorded in a field-dedicated logbook. Adjustments to the operating flowrates or pressures for sparged air or sparged propane were made if they deviated by more than $\pm 10\%$ of their target values.

Table 2. Schedule of Operation for Phases 1 and 2

Day	Task
<i>Construction and Mobilization</i>	
-65 to -42	Drilling and CAS installation
-44 to -40	Refurbishment of on-site GC
-51 to -47	10-h sparge test (air only)
-30 to -1	Develop analytical quality assurance/quality control (QA/QC)
0 ^(a)	Initiation of air sparging (air only)
<i>Start-Up and Phase 1</i>	
0-36	Establish background CAH levels; air distribution tests
36	Propane injection initiated at 2% in air
37-79	Monitored propane concentrations in saturated and vadose zones in both test plots. No air sparging.
81-124	Weekly propane injection (4 h at 4% propane).
125-170	Propane injections increased to twice weekly (4 h at 2% propane) to accelerate TCE/c-DCE bioremediation.
170-187	No propane or air added so that propane oxidation rates could be verified and compared to earlier rates to see if remediation would continue without additional propane.
188-243	Ammonia to active and control test plots (with propane & air in active test plot, air only in control test plot) at 0.01%, due to potential nitrogen limitation in the treatment zone.
244-392	Propane concentrations in the saturated and vadose zones were monitored. No air sparging.
<i>Phase 2</i>	
393-394	SF ₆ and pressure transducer tests conducted for Multi-Site ESTCP study; sparged at 10 scfm (air only) for 1 day.
398-401	Post-sparge baseline, beginning of Phase 2.
404-427	Weekly propane injection (4 h, 1% propane in air).
431-435	Conducted nitrogen push-pull tests in the vadose zone to see if vadose zone is nitrogen limited.
440-450	Weekly propane injections (4 h, 1% propane in air).
454-478	Weekly propane injections (4 h, 2% propane in air).
482	Sparged for 4 h at 4% propane. Increased sampling frequency to measure degradation kinetics.
485-503	Bi-weekly injection of 4% propane and 0.1% ethylene.
504-511	Ethylene monitoring in vadose & saturated zones, no sparging.
512-526	Weekly sparging with methane at 7.9 standard liters per minute (slpm).
527-545	Methane monitoring in vadose and saturated zones, no sparging.
546	Methane injection at 7.9 slpm.
588	Final groundwater and vadose zone sampling event.

(a) Day 0 is May 12, 1999.

3.5.2 Groundwater Sampling. Groundwater samples were collected weekly (approximately). Parameters measured included groundwater quality parameters, contaminant concentrations, DO, and propane. Sample collection included QA/QC samples, which included a check standard and a duplicate sample for every batch of 12 groundwater or soil gas samples. Prior to sampling, sampling point identification was checked and recorded along with the date and time in the field logbook. Groundwater samples were collected using in-well pneumatic bladder peristaltic pumps.

During Phase 2, the active test plot monitoring points that were sampled with the highest frequency were monitoring points MW-C2, MW-C3, and MW-C4 at the 117-ft depth interval. These monitoring points demonstrated the highest levels of propane-degrading and CAH cometabolic activities. Between Phases 1 and 2, all monitoring points at the 113-ft depth interval ran dry and were unable to be sampled for groundwater. Although unexpected, this was not necessarily surprising, because the groundwater in the Sacramento area is reported to drop as much as 1 ft per year. For this reason, the 113-ft interval groundwater monitoring points were not sampled during Phase 2.

3.5.3 Soil Gas Sampling. Soil gas was extracted from the vadose zone with a ¼-hp diaphragm pump. Soil gas was purged for two minutes, before sample collection and field parameters were measured. The diaphragm pump was run for 10 minutes to flush out the lines. A Tedlar™ bag was purged three times with the soil-gas before collection. Soil gas parameters included contaminant concentrations, oxygen, carbon dioxide, and propane; QA/QC samples also were included.

During Phase 1, the soil-gas monitoring points at the 85-ft and 95-ft depth were monitored weekly (approximately) in the active test plot. The 85-ft and 95-ft depth monitoring points in the control test plot were monitored approximately every two to three weeks, because much less activity was expected in the control test plot. Monitoring points in both test plots at the 30-ft depth and the 105-ft depth were monitored approximately every two to four weeks. During Phase 2, the sampling frequency was reduced to monthly for all monitoring points except the 95-ft-depth monitoring points in the active test plot, for which sampling was maintained weekly.

3.6 Analytical Procedures

Field measurements include depth to groundwater, DO, redox, pH, conductivity, turbidity and temperature, groundwater and soil-gas CAH concentrations, groundwater and soil-gas propane and methane concentrations, and soil-gas oxygen (O₂) and carbon dioxide (CO₂) concentrations. Analytical methods, sampling frequency, and sampling requirements for VOCs in Groundwater and Soil Gas are shown in Table 3.

Table 3. Analytical Methods and Sampling Frequency/Requirements for VOCs in Groundwater and Soil Gas

Analyte	Sample Location (Matrix)	On- or Off-Site Analysis	Frequency	Method or Instrumentation	Container Type	Container Size	Preservative	Holding Time
O ₂ /CO ₂	SGMP (vapor)	On	Weekly	GT 205	None	NA	NA	NA
Temp/dew point/relative humidity	SGMP (vapor)	On	Weekly	Hygrometer/ Thermometer Model 35519-041 (Control Corp)	None	NA	NA	NA
CAHs	SGMP (vapor)	On	Weekly	8021BM; HP GC Model 5890	Tedlar™	1 L	None	Same day
Propane/Methane/Ethylene	SGMP (vapor)	On	Weekly	8021BM; HP GC Model 5890	Tedlar™	1 L	None	Same day
DO/pH/Temp/Turbidity/Conductivity	GWMP (liquid)	On	Weekly	Horiba Model U-10	None	NA	NA	NA
CAHs	GWMP (liquid)	Phase 1: On Phase 2: Off	Weekly	SW 9-846 802BM; HP GC Model 5890	VOA vial	40-mL	Phase 1: 4°C Phase 2: one vial HCl, second vial H ₂ SO ₄	14 days
Propane/Methane/Ethylene	GWMP (liquid)	Phase 1: On Phase 2: Off	Weekly	SW 846 802BM; HP GC Model 5890	VOA vial	40-mL	Phase 1: 4°C Phase 2: one vial HCl, second vial H ₂ SO ₄	14 days
NO ₂ /NO ₃ /SO ₄	GWMP (liquid)	Phase 2: Off	Weekly	IC	VOA vial	40-mL	Phase 1: 4°C Phase 2: one vial HCl, second vial H ₂ SO ₄	14 days
Propane	Sparge well (vapor)	On	Continuous	Series 8800 Continuous Analyzer (Baseline Industries)	None	NA	NA	NA

SGMP = soil-gas monitoring point; GWMP = groundwater monitoring point

NA = not analyzed

3.6.1 Groundwater Quality Parameters. Groundwater quality parameters included redox, temperature, pH, turbidity, alkalinity, nitrate (NO_3^- -N), ammonia (NH_4 -N), and total Kjeldahl nitrogen (TKN). Samples were measured for DO, redox, pH, conductivity, turbidity, and temperature under continuous flow using a water quality meter (Horiba Model U-10). To minimize sample aeration, a continuous flowthrough cell was used to provide a sampling chamber for the meter.

The depth to groundwater in groundwater monitoring points was measured with a water-level probe (Solinst, Model 101 with P4 probe).

Groundwater samples for on- and off-site contaminant analyses were collected in 40 mL volatile organic analysis (VOA) vials with TeflonTM-coated septa-lined caps. The pH of the aqueous effluent samples was adjusted to a value of <2 with hydrochloric acid (HCl) to stabilize the organic species, and the samples were stored at 4°C until analysis. During Phase 2 of the demonstration, when HCl in the samples was observed to have interfered with nitrate/nitrite analyses, duplicate samples were taken at each monitoring point; one sample was preserved with HCl and the other with sulfuric acid (H_2SO_4). Sulfuric acid did not appear to hinder $\text{NO}_3^-/\text{NO}_2^-$ analyses. The VOA vials were stored at 4°C until analysis.

The following analytes were targeted for the on-site analyses: PCE; TCE; *c*-DCE; 1,1-DCE; CF; and 1,1-DCA. The selection of these compounds was based on the range of contaminants detected at OU A. Intermediate breakdown products, such as TCE epoxides, are highly unstable and will not remain in the groundwater long enough to be measured. Therefore, finding and measuring these breakdown products in groundwater and soil gas was not included in the scope of this study. Analytical methods are shown in Table 3.

Samples measured in the field were analyzed using a purge-and-trap GC method. Samples were identified and quantified against known standards. Liquid standards were prepared gravimetrically in an off-site laboratory and shipped to the site. These standards were stored at 4°C until use. They were diluted volumetrically on site using deionized water and were injected manually into the purge-and-trap for GC analysis. A minimum of one check standard was analyzed for every set of 15 purge and trap samples.

3.6.2 Soil-Gas Measurements. Soil gas samples were collected using pre-cleaned TedlarTM bags, which were carried to the field trailer for analysis. Samples were drawn from the bags using a hand-held syringe and were hand injected into the purge-and-trap autosampler for analysis. Soil gas was analyzed for VOCs using the GC-FID/PID in the USAF analytical trailer; target soil-gas VOCs were TCE, *c*-DCE, 1,1-DCE, 1,1-DCA, and CF. VOCs were identified and quantified against a standard mixture. Gas samples were analyzed using the purge-and-trap GC method.

Propane concentrations in soil gas were measured using the on-site GC-FID/PID in the USAF trailer (Hewlett Packard, Model 5890 Series II). The GC was calibrated against propane

standards, which were taken from a specialty gas cylinder provided for the project (Scott Specialty Gases, Plumsteadville, PA).

The temperature, dew point, and relative humidity of the soil gas were analyzed using a Control Company Digital Hygrometer/Thermometer Model 35519-041. A digital display showed the measurements within the sample instantaneously. The probe of the hygrometer/thermometer was placed in a stilling chamber comprised of a six-inch piece of SCH 40 PVC. The readings were taken after 10 minutes of purging the stilling chamber with fresh soil gas.

Gaseous concentrations of carbon dioxide and oxygen were analyzed using a GasTech series gas monitor Model 205, equipped with a digital display that shows continuous soil-gas concentrations.

4. Performance Assessment

For the purposes of this report, and to maintain brevity, Section 4 focuses on selected results and selected groundwater and soil-gas monitoring points at the active and control test plots that represent the typical activity observed during the experimental operating period. All the results are presented in the Final Report (Battelle, 2001), including the preliminary testing and tracer test results, neither of which are presented in this report.

4.1 Performance Data

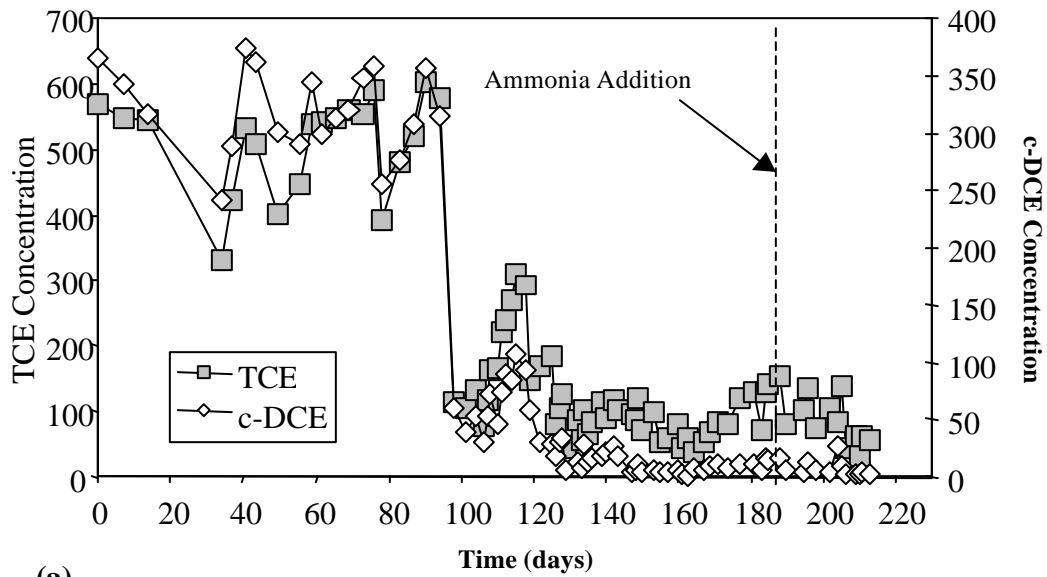
The CAS field demonstration was conducted for 540 days at McAFB. Throughout the study, site-specific CAH compounds were monitored in the saturated and vadose zones, to assess the extent of their remediation via the CAS process. These compounds included TCE, *c*-DCE, 1,1-DCE, CF, and 1,1-DCA.

TCE and *c*-DCE were the major contaminants in the groundwater and the vadose zone and primary focus was given to these compounds for remediation optimization. The remaining compounds were monitored as secondary compounds to assess the impact of the treatment process on multiple groundwater contaminants. Discussion of the results for 1,1-DCE, CF, and 1,1-DCA can be found in the Final Report (Battelle, 2001).

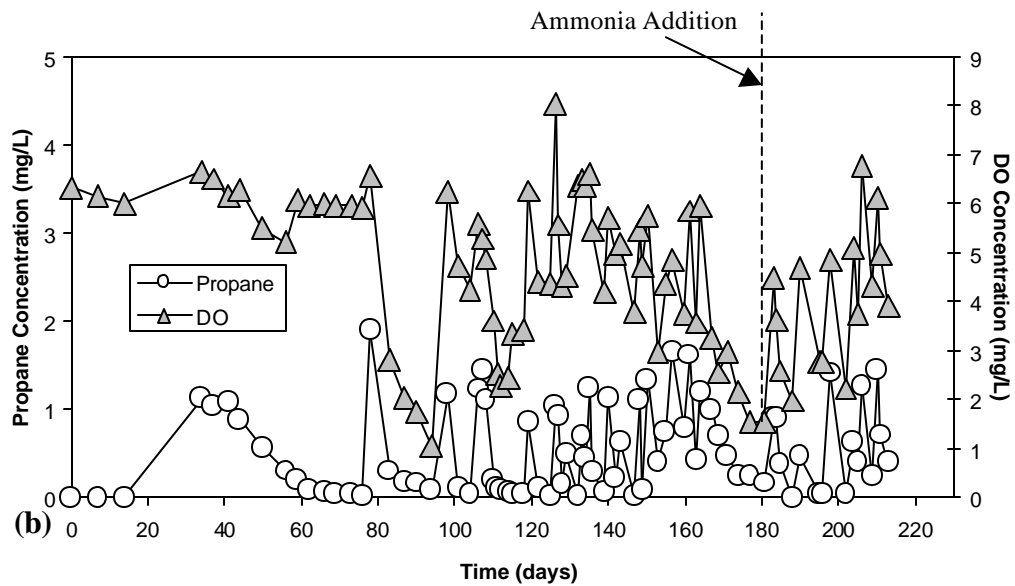
The field demonstration was divided into two phases. The first phase focused on the groundwater remediation and propane degradation along with CAH dechlorination. The second phase of the demonstration focused on propane degradation and CAH remediation in the unsaturated zone. These phases are described as Phase 1 and Phase 2, respectively. A detailed schedule of operating conditions and field observations is provided in the Final Report (Battelle, 2001).

4.1.1 CAS Results in Groundwater. Dissolved propane and oxygen concentrations and corresponding propane degradation rates in the saturated zone varied greatly, indicating some areas were more effectively sparged than others. For example, monitoring points MW-C4-113 and MW-C3-113 showed relatively high dissolved propane concentrations after each sparge event, between 1 and 3 mg/L. Much lower concentrations were measured in MW-C3-117 and only trace concentrations of propane were measured in MW-C1-113. The SF₆ data demonstrated similar results, where virtually no SF₆ was measured at monitoring points MW-C1-113/117, MW-C5-113/117, and MW-C6-113/117, and relatively low SF₆ concentrations were measured in MW-C2-113. Thus, it appears that the propane sparging did not reach every groundwater monitoring point, most likely due to soil heterogeneities.

Figure 6 shows results of propane sparging in MW-C6-113, during Phase 1. Propane and oxygen concentrations over time are shown in the bottom most figure, and CAH concentrations over time are shown in the upper most figure. Propane sparging was initiated on day 36. A 50-day (Days 36 to 86) lag period was observed before propane utilization was evident in



(a)



(b)

Figure 6. Groundwater Monitoring Point MW-C4-113 in the Active Test Plot; (a) TCE and *c*-DCE Concentrations Over Time and (b) Propane and DO Concentrations Over Time

the saturated zone; this is most evident in monitoring point MW-C4-113, but also was seen in monitoring points MW-C3-113 and MW-C3-117 (Section 5 of the Final Report; Battelle 2001).

With successive propane additions, the rate of propane utilization increased as the microbial population was stimulated (Figure 6). DO concentrations closely matched these patterns, demonstrating a direct correlation between oxygen and propane utilization for each successive sparge event. Each sparge event resulted in elevated DO levels, followed by decreased DO levels when propane was degraded. These results demonstrated that propane was effectively degraded in the aquifer.

A wide range of contaminant concentrations was seen in initial groundwater samples (Table 4). Higher concentrations occurred in the active than the control test plot, and much higher TCE concentrations were seen in both test plots than *c*-DCE concentrations. TCE and *c*-DCE in the groundwater in the active test plot ranging from 100 to 1,000 µg/L, compared to the control test plot where concentrations ranged from 60 to 400 µg/L. Only trace 1,1-DCE concentrations were detected, and only in the control test plot, while 1,1-DCA and CF were not detected. The presence of very low 1,1-DCE, 1,1-DCA, and CF concentrations was observed when the site was first being assessed for this study. Their disappearance before the study began may be due to initial air sparging activity conducted during the helium tracer test.

In the active test plot, the highest TCE and *c*-DCE removal rates occurred in the monitoring points that received the highest propane concentrations, as seen in MW-C6-113 (Figure 6). Five of the 12 groundwater monitoring points in the active test plot showed significant propane and oxygen utilization and corresponding TCE and *c*-DCE removals, while the other six monitoring points were ineffectively sparged due to soil heterogeneities and did not receive adequate propane to cometabolically degrade the TCE and *c*-DCE.

Much less effective CAH removal was observed in the control zone, near wells where SF₆ results showed that areas were effectively sparged. For example, Figure 7 shows sparging results in MW-A1-113, in the control zone, which did not receive propane. Sparging resulted in elevated DO concentrations, which did not decrease like they did in the active zone, because there was no measurable biological activity. CAHs declined much more slowly, over a 160-day period, and to final concentrations that were higher than in the active zone, as was shown in Figure 6. CAH removal was negligible in wells the control site (Figure 7) and in wells that received negligible sparging due to soil heterogeneities in the active site (Figure 8). Confirmation that the well in Figure 8 (MW-A2-117) was ineffectively sparged was obtained from the results of the SF₆ tracer study (Battelle, 2001).

Final CAH concentrations in the active and control test plots after approximately 200 days of operation are shown in Table 5. The table shows average values over the last 20 days of the Phase 1 operating period; the number of values averaged for each monitoring point is identified in the table. The last 20 days were used instead of simply recording the last data point, because this was thought to be more representative of the steady-state operation achieved in the system. Day to day fluctuations made using the last data point for each monitoring point impractical.

Table 4. Initial Groundwater CAH Concentrations^(a) Measured During the First 36 Days of Operation (Before Propane Sparging)

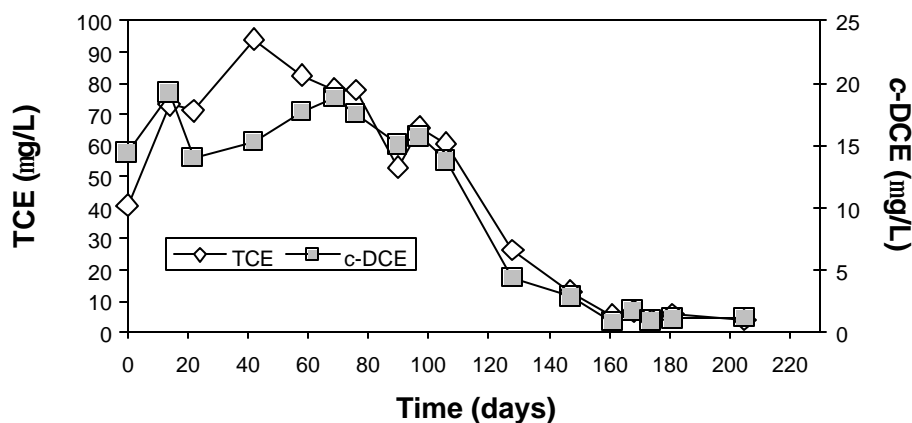
Monitoring Point	Depth	Contaminant Concentration (mg/L)				
		TCE	c-DCE	1,1-DCE	1,1-DCA	CF
Active Test Plot						
C1	113	944 ± 170	511 ± 153	< 0.27	< 0.204	< 0.284
	117	604 ± 33	286 ± 13	< 0.27	< 0.204	< 0.284
C2	113	431 ± 46	193 ± 20	< 0.27	< 0.204	< 0.284
	117	61 ± 11	14 ± 1.6	< 0.27	< 0.204	< 0.284
C3	113	535 ± 127	238 ± 50	< 0.27	< 0.204	< 0.284
	117	131 ± 9.1	21 ± 1.1	< 0.27	< 0.204	< 0.284
C4	113	555 ± 14	342 ± 24	< 0.27	< 0.204	< 0.284
	117	281 ± 13	107 ± 10	< 0.27	< 0.204	< 0.284
C5	113	2500 ± 196	2095 ± 156	< 0.27	< 0.204	< 0.284
	117	250 ± 15	75 ± 6.7	< 0.27	< 0.204	< 0.284
C6	113	NA				
	117	355 ± 8.9	93 ± 4.2	< 0.27	< 0.204	< 0.284
Average		604 ± 58	361 ± 40	< 0.27	< 0.204	< 0.284
Control Test Plot						
A1	113	62 ± 18	16 ± 2.9	< 0.27	< 0.204	< 0.284
	117	20 ± 8.6	8.0 ± 0.99	< 0.27	< 0.204	< 0.284
A2	113	83 ± 23	11 ± 1.1	< 0.27	< 0.204	< 0.284
	117	356 ± 15	27 ± 3.3	14 ± 12	< 0.204	< 0.284
A3	113	222 ± 36	47 ± 5.8	< 0.27	< 0.204	< 0.284
	117	227 ± 24	18 ± 5.9	8.7 ± 7.7	< 0.204	< 0.284
A4	113	612 ± 134	72 ± 8.9	< 0.27	< 0.204	< 0.284
	117	72 ± 3.2	2.6 ± 2.2	< 0.27	< 0.204	< 0.284
A5	113	168 ± 72	35 ± 8.4	< 0.27	< 0.204	< 0.284
	117	259 ± 7.9	17 ± 4.1	12 ± 5.7	< 0.204	< 0.284
A6	113	374 ± 30	132 ± 44	< 0.27	< 0.204	< 0.284
	117	292 ± 25	14 ± 2.6	14 ± 2.8	< 0.204	< 0.284
Average		230 ± 33	33 ± 8	4 ± 2	< 0.204	< 0.284

(a) Each monitoring point and depth had three samples taken during the 36 days the background was established.

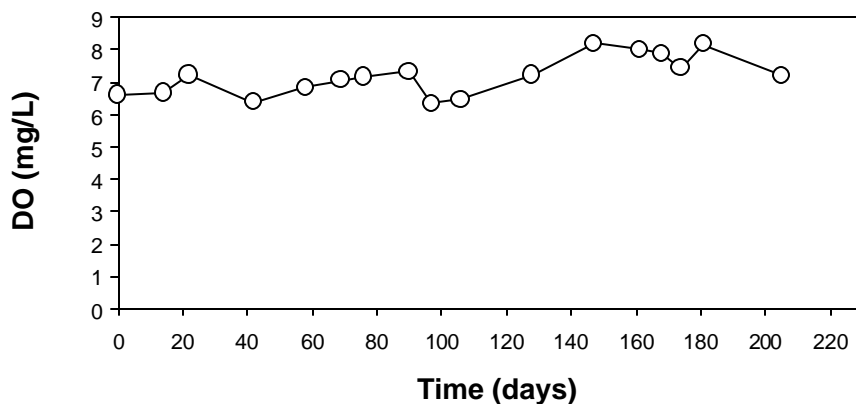
NA = not analyzed.

“<” means below reported detection limit.

C6-113 was not analyzed because it went dry during the experiment.



(a)

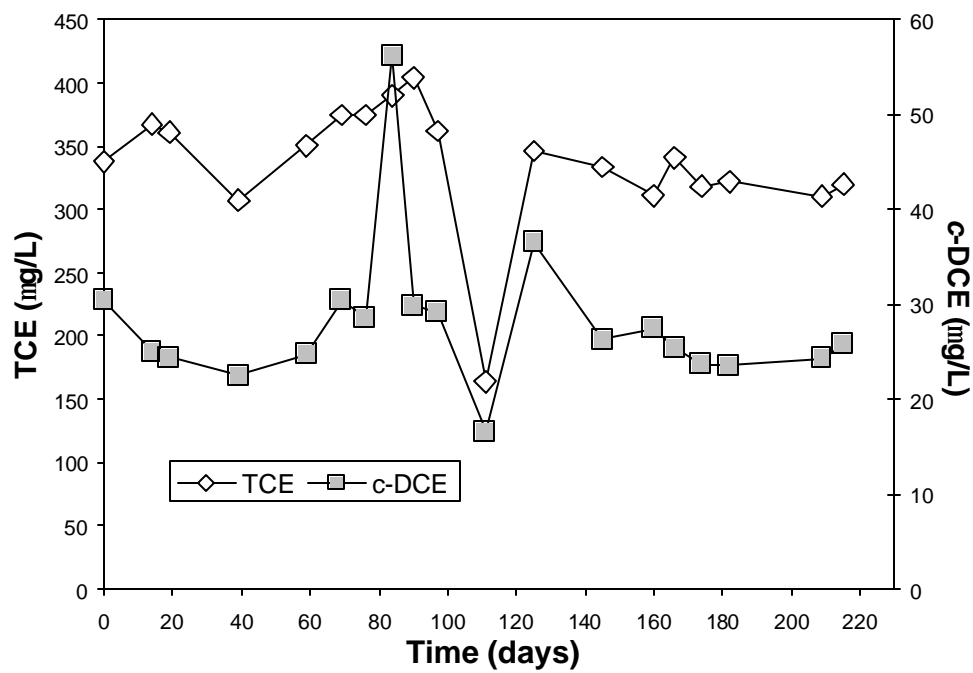


(b)

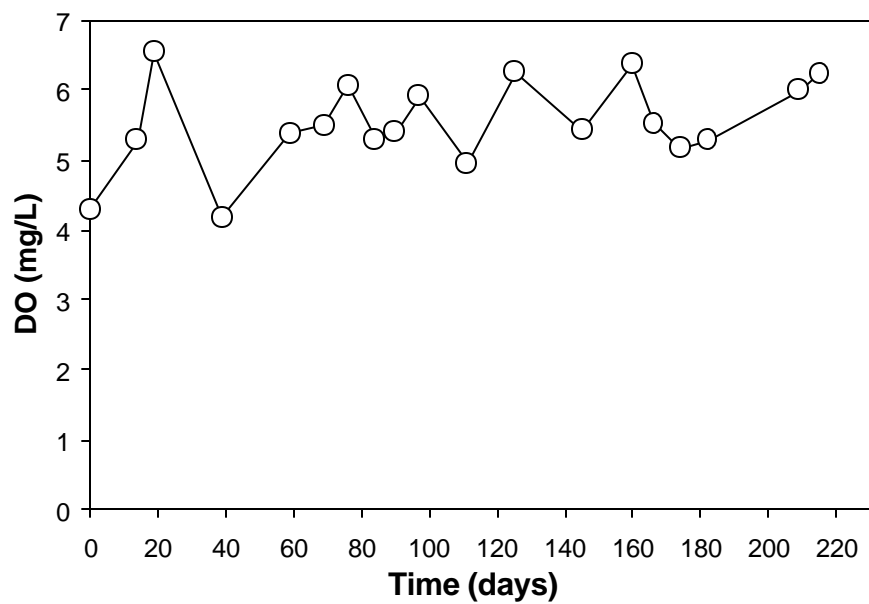
Figure 7. Groundwater Monitoring Point MW-A1-113 in the Control Test Plot; (a) TCE and *c*-DCE Concentrations Over Time and (b) DO Concentrations Over Time

Shaded portions of the table correspond to monitoring points where SF_6 concentrations were less than 10% saturation following the SF_6 tracer test. Such low SF_6 concentrations would suggest that these monitoring points were ineffectively sparged.

Except for MW-C3-113, final TCE concentrations in the active test plot ranged from 5.9 to 67 $\mu\text{g/L}$; the final MW-C3-113 groundwater averaged 371 $\mu\text{g/L}$. Similarly, *c*-DCE concentrations were low in the active test plot; final *c*-DCE concentrations ranged from 0.92 to 6.7 $\mu\text{g/L}$, except for MW-C3-113 where *c*-DCE concentrations averaged 56 $\mu\text{g/L}$. The reason for the high residual TCE/*c*-DCE concentrations in MW-C3-113 is unknown. The monitoring point appeared to receive propane to support propane degradation and subsequent CAH cometabolism. One possibility could be that this monitoring point had a greater influx of CAHs during testing, resulting in the replenishment of the degraded CAH fraction. Another possibility is that MW-C3-113 represents the low-end range of activity that could be expected for the CAS process.



(a)



(b)

Figure 8. Groundwater Monitoring Point MW-A2-117 in the Control Test Plot; (a) TCE and c-DCE Concentrations Over Time and (b) DO Concentrations Over Time

Table 5. Phase 1 CAH Concentrations During the Final 10 Days Of Phase 1 Operation

Monitoring Point	Depth	No. of Samples	Contaminant Concentration (µg/L)				
			TCE	c-DCE	1,1-DCE	1,1-DCA	CF
Active Test Plot							
C1	113	1	1514	1876	15	131	87
	117	1	1305	1089	11	91	30
C2	113	7	336 ± 13	57 ± 3.4	2.5 ± 2.3	5.6 ± 0.28	12 ± 6.3
	117	7	5.9 ± 3.8	0.92 ± 1.3	2.7 ± 4.8	< 0.204	2.8 ± 3.6
C3	113	7	371 ± 53	56 ± 11	2.2 ± 4.4	6.1 ± 1.3	6.8 ± 1.2
	117	7	12 ± 6.9	3.7 ± 7.6	1.8 ± 1.1	0.16 ± 0.42	6.2 ± 8.5
C4	113	7	67 ± 35	6.7 ± 9.2	3.5 ± 2.9	0.91 ± 0.62	9.9 ± 13
	117	7	38 ± 7.2	2.4 ± 0.76	2.8 ± 3.1	0.30 ± 0.14	5.6 ± 0.69
C5	113	1	1635	1834	18	144	92
	117	1	591	210	< 0.27	14	34
C6	113	NA					
	117	1	445	335	9.0	25	65
Average ^(a)			99 ± 21	14 ± 6.0	2.6 ± 3.3	1.5 ± 0.50	6.3 ± 5.4
Control Test Plot							
A1	113	1	4.0	1.2	< 0.27	< 0.204	< 0.284
	117	2	9.3 ± 0.52	1.7 ± 2.3	< 0.27	< 0.204	1.9 ± 3.2
A2	113	1	29	4.0	3.6	0.86	< 0.284
	117	2	315 ± 6.6	25 ± 1.1	< 0.27	16 ± 0.16	18 ± 26
A3	113	1	61	29	1.8	1.6	15
	117	2	186 ± 8.7	10 ± 1.2	11 ± 15	7.8 ± 0.95	5.1 ± 0.56
A4	113	1	175	27	< 0.27	8.4	17
	117	2	185 ± 2.8	9.3 ± 0.17	9.1 ± 13	6.2 ± 0.15	13 ± 12
A5	113	1	190	31	11	12	< 0.284
	117	2	119 ± 0.42	6.4 ± 0.02	6.4 ± 9.0	3.4 ± 0.29	11 ± 8.8
A6	113	1	55	24	3.0	1.5	< 0.284
	117	2	126 ± 1.5	7.3 ± 1.0	5.0 ± 7.0	3.8 ± 0.06	12 ± 2.3
Average ^(a)			92	18	3.3	4.6	6.4

(a) Average values were based on the active (i.e., unshaded) monitoring points only, based on the SF₆ test.

“<” means below reported detection limit.

C6-113 was not analyzed because it went dry during the experiment.

Significant mass removal also was observed in the control test plot, indicating that contaminants were removed by air stripping only. Because the contaminant mass loading was much higher in the active test plot than the control test plot (the average initial TCE concentration in the active site was 604 mg/L compared to 230 mg/L in the control test plot), the CAS process in the active site resulted in a larger overall removal of mass than the air sparging alone. However, the fact that the final concentrations were similar may suggest that the CAHs reached low-concentration

plateaus over time. Such plateaus would be influenced by the rate of contaminant removal, the sorption of contaminants on natural organic matter, and the incoming flux of fresh contaminants from upstream of the treatment area.

Nitrate was found to be limiting in the groundwater during the Phase 1 operating period, potentially limiting propane degradation and cometabolic TCE and *c*-DCE transformations. Microcosm testing indicated that low nitrogen levels could limit propane utilization and subsequent CAH degradation. During Phase 2, propane feed concentrations were lowered to approximately 1% of the sparge air. This lowered feed concentration resulted in sustaining nitrate levels in the groundwater at approximately 1 to 4 mg/L.

The system was inactive between December 17, 1999 and May 4, 2000. After this time, two complete rounds of baseline sampling took place, including groundwater and soil gas samples. This baseline set of samples was used to measure the rebound since the end of the Phase 1 experiment and to establish the initial propane and CAHs concentrations at the beginning of Phase 2. Groundwater CAH concentrations increased consistently during the 4.5-month rebound period. The increased CAH could have been due to the influx of CAH-contaminated groundwater into the system or the desorption of CAH from soils in the active test plot. However, nitrate concentrations also increased, suggesting that the change in CAH concentrations were due at least in part to the influx of groundwater from outside the treatment area.

Sparging in Phase 1 was conducted at 10 scfm with 2 to 4% propane in the sparge gas. Phase 2 attempted to optimize the sparging by reducing the sparge rate and the propane concentrations in the injected air. It was thought that reduced propane concentrations would (a) exert less of a demand on nitrate levels, (b) allow propane concentrations to be depleted to lower levels between sparge events to permit more efficient CAH cometabolism (propane and CAHs compete for monooxygenase activity and the presence of propane could have inhibited CAH cometabolism), and (c) to maintain higher residual dissolved oxygen levels between sparge events to promote more efficient CAH cometabolism. The system was sparged with 5 scfm of air with 1% propane for 4 hours once a week from June 19, 2000 to July 25, 2000. Because propane in the groundwater seemed to be disappearing quickly during this period, the groundwater appeared to have excess capacity to degrade propane. Hence, the propane injection concentration was increased to 2%; from July 25 to September 5, 2000, the system was sparged with 5 scfm of air containing 2% propane for 4 hours once a week. At this point, the system seemed to be optimized and steady state propane and CAH degradation was achieved.

A summary of average CAH concentrations at the end of the propane- and methane-stimulation periods for Phase 2 is shown in Table 6. Only the shallow monitoring points in the control test plot are shown, because the deeper monitoring points did not show significant SF₆ levels during the tracer testing, indicating that they were ineffectively sparged. Furthermore, only effectively sparged wells in the active zone are shown, eliminating both those that did not show significant SF₆ levels during the tracer test, and the 113-ft elevation wells, which were no longer submerged during Phase 2 due to a significant drop in the groundwater table between Phases 1 and 2.

Table 6. Groundwater CAH Concentrations at the End of Propane Injection and End of Methane Injection for Monitoring Points that Show Activity

GW MW	No. of samples	Contaminant Concentration (mg/L)				
		TCE	c-DCE	1,1-DCE	1,1-DCA	CF
Summary for active monitoring points in the control test plot						
A1-113	5	4.6 ± 2.8	1.4 ± 1.1	< 0.27	< 0.204	< 0.284
A2-113	5	93 ± 59	12 ± 7.5	0.79 ± 0.51	1.4 ± 2.1	< 0.284
A3-113	2	206 ± 218	30 ± 22	1.1 ± 1.6	4.9 ± 6.9	< 0.284
A4-113	5	474 ± 166	53 ± 13	4.1 ± 1.8	10 ± 2.3	< 0.284
A5-113	4	22 ± 15	3.8 ± 2.6	< 0.27	< 0.204	< 0.284
Summary of last 14 d of 2% propane injection of active monitoring points in active test plot						
C2-117	8	1.9 ± 1.7	< 0.278	< 0.27	< 0.204	< 0.284
C3-117	8	8.5 ± 2.5	0.04 ± 0.11	0.69 ± 0.97	< 0.204	< 0.284
C4-117	8	20 ± 6.0	1.5 ± 0.67	3.7 ± 4.8	< 0.204	< 0.284
Summary of last 20 d of methane injection of active monitoring points in the active test plot						
C2-117	5	6.2 ± 4.0	0.08 ± 0.13	0.09 ± 0.14	< 0.204	< 0.284
C3-117	5	22 ± 8.1	0.13 ± 0.15	< 0.27	0.03 ± 0.06	< 0.284
C4-117	5	19 ± 13	0.96 ± 0.88	0.21 ± 0.20	0.03 ± 0.06	< 0.284

“<” means below reported detection limit.

NA = not analyzed

In the active test plot, trace or nondetectable c-DCE concentrations were measured, and TCE concentrations were very low, averaging 1.9, 8.5, and 20 µg/L in the three most active monitoring points. Only non-detectable or trace 1,1-DCE, 1,1-DCA, and CF concentrations were measured. During propane feeding, the CAH concentrations in the active zone were consistently lower than in the control zone, indicating that cometabolism by propane-degrading bacteria more effectively reduced CAH concentrations in groundwater than stripping alone through sparging.

Except for 1,1-DCE, CAH concentrations increased during the period of methane injection into the aquifer. These results may suggest that either methane was a less effective growth substrate for CAH cometabolism, or more likely that the population of methanotrophs was not as high as the propane-degrading population, due to the much shorter feed period for methane.

4.1.2 CAS Results in the Vadose Zone. During Phase 1, there was no sign of propane degradation in the vadose zone, and consequently no sign of CAH degradation, as reported in the Final Report (Battelle, 2001). Propane degradation and cometabolic activities were monitored during Phase 2. Vadose zone propane and CAH concentrations in two soil-gas monitoring points

(SG-C1-95 and SG-C3-95) are shown in Figures 9 and 10, respectively. Both wells showed very stable propane and CAH concentrations over the 200-day monitoring period during propane feeding. The slow increase in CAH concentrations in SG-C3-95 may have been due to the migration of CAHs into the vicinity of SG-C3-95 from higher nearby concentrations in the vadose zone, or from stripping from the saturated zone. Similar results were seen in the control test plot, where CAH concentrations were very stable and showed no sign of degradation.

Methane first appeared in the vadose zone soon after it was injected with the sparge gas. Methane was rapidly degraded at both monitoring points, followed immediately by the first signs of propane degradation. The immediate degradation of propane to nondetectable levels following methane injection into the aquifer (Figures 9 and 10) was surprising, and suggested that either methane stimulated the direct degradation of propane or that propane was degraded cometabolically by the growth of methanotrophs in the vadose zone.

TCE concentrations in SG-C1-95 remained very stable, and *c*-DCE concentrations showed decreasing concentrations between Days 510 and 590, after methane was introduced into the aquifer. Much more significant decreases in both TCE and *c*-DCE concentrations were observed in SG-C3-95, in which concentrations were below detection limits for both compounds by the time of the last sampling event on Day 590. SG-C3-95 was the only soil-gas monitoring point that showed complete CAH removal with the introduction of methane into the sparge gas.

The fact that propane and CAHs disappeared in SG-C3-95 strongly suggests that the CAHs were degraded cometabolically by methanotrophs (or propane-degrading bacteria if propane was not cometabolically degraded) in the vicinity of this soil-gas monitoring point. Although it is possible that clean soil gas migrated into the area, thereby displacing the CAHs in the vadose zone near SG-C3-95, the stable concentrations monitored in virtually all the deep soil-gas monitoring points for more than 500 days suggests that the CAHs did not disappear through displacement alone, and that biodegradation likely played a major role in their disappearance. Limited time did not permit confirmation of these results, nor did it permit the continued methane addition and monitoring to promote CAH cometabolism near the other soil-gas monitoring points. Thus, it was not possible to confirm whether CAH cometabolism would have ensued after repeated methane injections and the stimulation and growth of methanotrophs throughout the vadose zone, or whether the degradation of CAHs near SG-C3-95 was an isolated event.

4.2 Performance Criteria

Performance criteria were met, in so far as the CAS process was able to meet MCLs in selected groundwater monitoring wells. However, as long as an incoming flux of contaminated groundwater persists at this site, the CAS process will have to be maintained in order to maintain low groundwater CAH concentrations. Rebound between Phases 1 and 2 showed, not surprisingly, that CAH removal was not permanent in the presence of incoming CAH compounds.

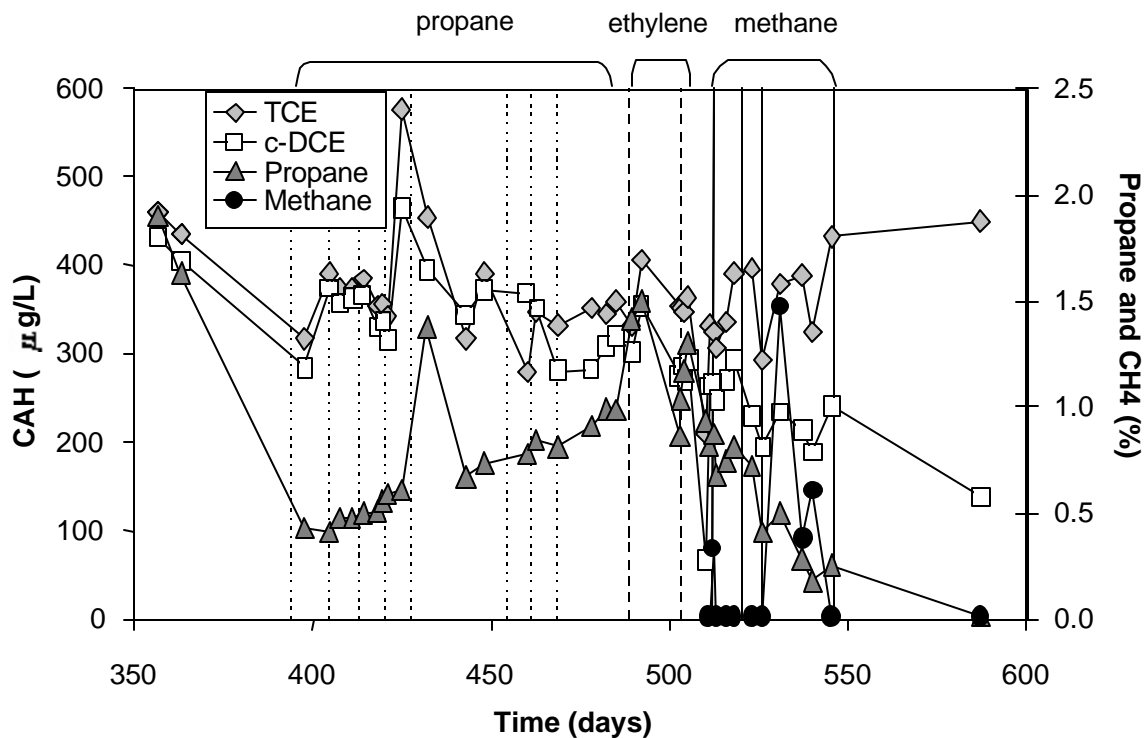


Figure 9. Active Test Plot Soil Gas CAH, Propane, and Methane in SG-C1-95

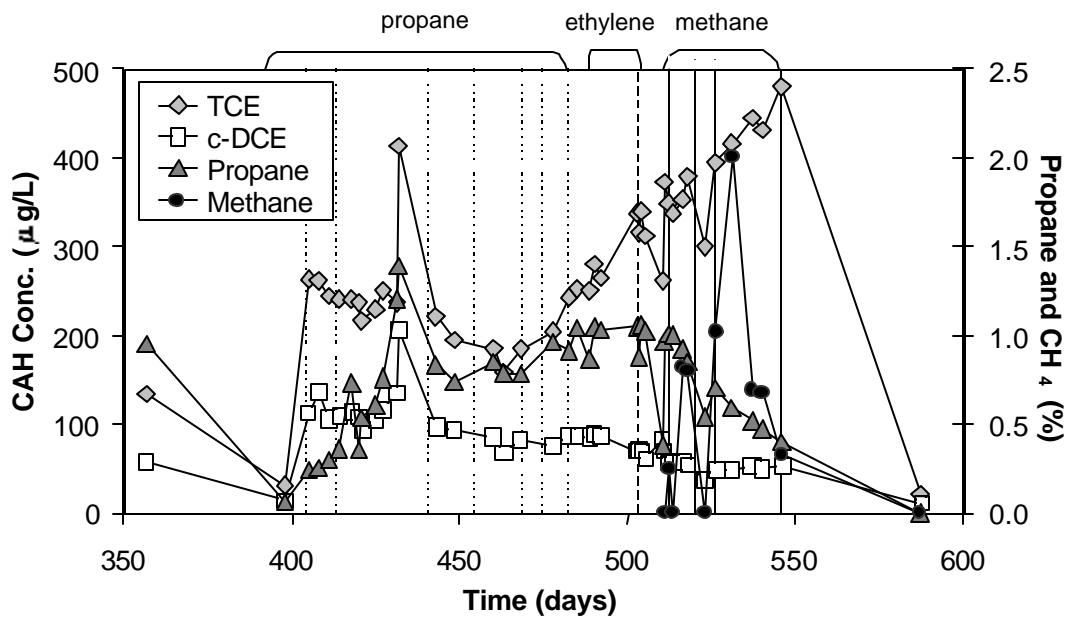


Figure 10. Active Test Plot Soil Gas CAH, Propane, and Methane in SG-C3-95

4.3 Data Assessment

The data described in Section 4 provide a realistic assessment of the demonstration objectives at McAFB. Figures and results were shown for CAS performance in groundwater and the vadose zone and demonstrated that CAS is effective and very competitive with air stripping in the saturated zone. The data indicated that CAS was ineffective in the vadose zone within the time frame of this study, necessitating a careful cost-benefit analysis for implementation at this site. The inability to stimulate cometabolism in the vadose zone at McAFB is not indicative of results at other sites; therefore, this would have to be examined during pilot testing.

The difficulty in stimulating propane degradation and subsequent CAS cometabolism in the vadose zone was not anticipated by the researchers in this study. For this reason, early microcosm studies focused on stimulating propane degradation and cometabolism in soil and groundwater samples from the saturated zone but neglected to study their properties in unsaturated vadose zone samples. In hindsight, and in anticipation of implementing this technology at other sites, it is imperative to confirm the presence of cometabolic activity in both the saturated and vadose zones using microcosms before implementing the technology in the field.

Researchers at U.S. EPA NRMRL, Cincinnati, OH, have effectively demonstrated the cometabolic bioventing process using propane as the cometabolic growth substrate, for vadose zone soils at Dover AFB (Sayles, 2000). At Dover AFB, propane uptake was rapid, and TCE concentrations were relatively low, typically about 1 ppmv with a few samples up to 20 ppmv.

When conducting a similar study at Hill AFB, the same researchers were unable to stimulate propane degradation and cometabolic CAH degradation in the vadose zone, despite successful microcosm studies that demonstrated propane degradation using the Hill AFB soils (Sayles, 2000). One significant difference between Dover AFB and Hill AFB conditions was the CAH concentration at each base. Concentrations at Hill AFB were around 1000 ppmv. Using Henry's law, 1000 ppmv would equate to approximately 300 mg/L (solubility is approximately 1,100 mg/L). Dr. Sayles and his coworkers speculate that their inability to stimulate propane degradation at Hill AFB is attributed to the high TCE concentrations in the vadose zone, resulting in high aqueous phase concentrations in the vadose zone porewater and potentially toxic conditions for propane-degrading bacteria.

TCE concentrations in the vadose zone at McAFB were approximately 400 to 800 µg/L, and *c*-DCE concentrations were approximately 300 to 600 µg/L. Using dimensionless Henry's law constants of 0.3 and 0.1 for TCE and *c*-DCE, respectively (Verschueren, 1996), the vadose zone gas-phase concentrations equate to approximately 1.3 to 2.7 µg/L TCE and 3 to 6 µg/L *c*-DCE in the aqueous phase of the vadose zone (i.e., vadose zone moisture). Although these concentrations are much lower than those observed at Hill AFB, they are higher than the concentrations at Dover AFB where vadose zone oxidation of propane and CAH cometabolism was successful.

There are two possible explanations of why propane degradation was not observed in the vadose zone at McAFB. The first explanation is that the bacteria were not present in the vadose zone. The second explanation is that conditions were not suitable for their growth. The potential for CAH toxicity, and the potential that nitrate also was limiting (nitrate was consistently observed as a limiting factor in groundwater), suggests that conditions may not have been suitable for the propane degraders in the vadose zone at this site.

The observation that CAHs were degraded in the vadose zone following methane addition to the sparge gas suggests that methanotrophs were not hindered by either of these factors. These results suggest that cometabolic CAH degradation in the saturated and vadose zones could be achieved at McAFB, although multiple growth substrates may be required for different treatment zones. There may be no single compound that is best suited for any given site. Rather, the use of a suite of compounds may be necessary and could optimize the potential for CAH remediation. Methanotrophs also are unique because they can fix nitrogen more readily than propane degrading bacteria. This gives them a unique advantage in the vadose zone where nitrogen gas is readily available but where other nitrogen sources may be limited due to the low water content in the soils. Such nitrogen limitations may have limited propane degradation in the McAFB vadose zone. Thus, a cometabolic strategy may be one that includes a combination of propane sparging and methane sparging, either simultaneously or in sequence. Experience at McAFB suggests that low gaseous concentrations are effective (e.g., less than 2 to 4%).

4.3.1 Regulatory Standards Attained for Cleanup. Regulatory standards (i.e., MCLs) were attained for CAHs at various sparged wells. The continuous influx of contaminated groundwater continuously stressed the system. Despite this, groundwater contaminant concentrations were consistently maintained at low levels. However, there were some wells where final concentrations did not achieve MCLs. Thus, although MCLs could be achieved, the influx rate of contaminated groundwater appeared to exceed the rate of CAH degradation to MCLs at the wells that did not achieve MCLs. This could easily be overcome at full scale by installing more wells, and by creating a barrier to control the downgradient flux of contaminated groundwater. Thus, this technology should be effective at attaining groundwater cleanup standards.

4.3.2 Personnel/Training Requirements. This demonstration showed that specialized personnel training requirements were not required for on-site operation of the CAS system. The Battelle and Oregon State University (OSU) on-site operators received no specialized training to operate and monitor the CAS system, besides the startup training provided by experienced Battelle operators. However, the principal investigators at Battelle (Dr. Andrea Leeson and Dr. Victor Magar) and OSU (Dr. Lew Semprini, Dr. Mark Dolan, and Dr. Mohammad Azizian) did provide in-depth knowledge of the microbiology of propane-degrading bacteria, methanotrophs, and the cometabolic process. The effective application of this technology does require microbiological knowledge, specifically of CAH cometabolism. The combined field experience of the principal investigators also led to more effective testing of this technology.

4.3.3 Health and Safety Requirements. CAS introduces significant safety requirements due to the introduction of a potentially explosive gas mixture to the subsurface. Precautions must be

taken to prevent a potentially explosive incident from occurring and from preventing the migration of this explosive gas mixture to the surface, especially in the presence of buildings, underground utilities, and other enclosed spaces.

Other than the use of a flammable gas, health and safety requirements for the CAS technology are comparable to conventional air sparging, which are minimal, unless subsurface structures or buildings are within the zone of influence of the air sparging system. In these situations, care must be taken that vapors are not pushed into these structures, potentially causing explosive or toxic environments.

4.3.4 Ease of Operation. The CAS technology is easily operated and requires minimal operating experience. Oversight by an engineer with knowledge of the cometabolic microbial process and air sparging technology is necessary.

4.3.5 Limitations. Technology limitations are discussed in Section 2.3.

4.4 Technology Comparison

The CAS technology may be compared to conventional P&T, which is known to require decades to remediate aquifers contaminated with CAHs, or it may be compared with conventional air sparging combined with SVE and off-gas treatment. Cost savings using CAS would be realized because CAS would remove the requirement for aboveground water or off-gas treatment, thereby potentially reducing long-term operation and maintenance costs. All three technologies (P&T, air sparging, and CAS) are expected to be able to achieve MCLs in groundwater. CAS and air sparging would be very competitive in their ability to achieve groundwater MCLs, because both would rely on stripping contaminants from groundwater, in part or in whole. CAS would have an advantage over conventional air sparging because it could rely on both the stripping mechanism in addition to in situ CAH biodegradation.

A comparison of CAS and SVE for vadose zone remediation could not be made at the McAFB site, because propane could not be degraded in the vadose zone. However, assuming both technologies are comparably effective, a cost comparison between these technologies is made in Section 5.

5. Cost Assessment

This section discusses the cost considerations involved in the application of cometabolic air sparging. Discussed in the following sections are cost reporting for the demonstration and for a full-scale implementation of the demonstration, a cost analysis, and a cost comparison.

5.1 Cost Reporting

Implementation costs for the CAS effort at McAFB are shown in Table 7. Costs include fixed and variable costs, and estimated funding by McAFB. McClellan AFB in-kind funding paid for the drilling of all monitoring and operating wells, fencing for security, water and power, and waste disposal. Various major costs included on-site labor for the continuous operation and maintenance (O&M) and sampling of the system, and for the significant analytical load of the demonstration. Much lower costs would be expected, under full-scale implementation as shown in Table 8, which shows the estimated full-scale demonstration costs for a full-scale demonstration, for a 30-ft by 20-ft by a 130-ft deep site, with 20 feet of groundwater contamination between 100 and 120 ft bgs.

5.2 Cost Analysis

The major cost drivers for CAS are drilling and installation, O&M, and monitoring. A cost sensitivity analysis was conducted by adjusting the following cost variables:

- The sparge radius of influence could be increased if justified based on the results of tracer testing studies. The sparge radius of influence was adjusted from 15 to 25 ft, resulting in a reduction of sparge wells from 5 wells to 3 wells for the assumed treatment area;
- The vadose zone depth was reduced from 100 ft to 20 ft. This reduced the depth of the sparge and monitoring wells;
- The test duration was adjusted from an assumed 2-year duration to 1 and 5 years, respectively.

Results of the cost sensitivity analysis are shown in Table 9. The table shows impacted costs and a revised cost per unit volume (\$/yd³) for each variable condition. Results of the cost comparison indicate that treatment duration and vadose zone depth have the greatest impact on unit treatment costs, while the reduction in the number of sparge wells is much smaller. The lowest cost was \$141/yd³ for a 1-year CAS effort and the highest cost was \$201/yd³ for the 5-year treatment effort. Thus, accurate prediction of the time for remediation is important for an accurate estimate of the project costs.

Table 7. McClellan AFB, California Demonstration Costs

Cost Category	Sub Category	Costs (\$)
FIXED COSTS		
1. CAPITAL COSTS	Mobilization/demobilization	\$16,000
	Planning/Preparation	\$24,000
	Site investigation and testing	
	- Nutrient Addition Testing	\$16,500
	- Microcosm Study – field work	\$16,000
	- Other	\$8,000
	Equipment Cost	
	- Total hydrocarbon analyzer	\$16,000
	- Oil-less air compressor	\$12,500
	Start-up and Testing	\$10,000
	Other	
	- Non process equipment	\$20,600
	- Installation	\$30,000
	- Engineering	\$20,000
	- Management Support	\$15,000
Sub-Total		\$204,600
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Labor	
	- Field personnel – on-site	\$90,000
	- Battelle personnel – on-site	\$25,000
	- Travel	\$24,000
	- OSU on-site lodging	\$16,000
	Materials and Consumables	\$16,000
	Utilities and Fuel	\$300
	Equipment Rentals	
	- 2 Conex boxes	\$3,500
	- Analytical tank rentals	\$4,000
	- Other rentals	\$3,400
	Performance Testing/Analysis	
	- Outside lab analysis	\$4,300
	- Battelle lab & data analyses	\$15,000
	- Field GC work	\$19,000
	- Other	\$2,300
	Other direct costs	\$400
	Oregon State University ^(a)	\$264,000
*McClellan AFB in-kind funding (drilling, fencing, power/water, waste disposal)		\$200,000
Sub-Total		\$687,200
TOTAL COSTS		
TOTAL TECHNOLOGY COST: \$891,800		
Quantity Treated: 523 yd ³		
Unit Cost (\$): \$1,705/yd ³		

(a) Oregon State University conducted microcosm studies, assisted with field studies, and analyzed aqueous samples during Phase 2

Table 8. Estimated Full-Scale Implementation Costs for Conducting Cometabolic Air Sparging at McClellan AFB, California ^{(a)(b)}

Cost Category	Sub Category	Costs (\$)
FIXED COSTS		
CAPITAL COSTS	Mobilization/demobilization	\$50,000
	Planning and Preparation	\$40,000
	Site Investigation	
	- Microcosm	\$50,000
	- Pilot Testing	\$36,500
	Equipment Cost	
	- Oil-less air compressor	\$20,000
	- Total hydrocarbon analyzer	\$26,000
	Start-up and Testing	\$17,000
	Other	
	- Propane Tank	\$5,000
	- Installation	\$49,500
	- Engineering	\$20,000
	- Management Support	\$15,000
Sub-Total \$319,000		
VARIABLE COSTS		
OPERATION AND MAINTENANCE	Labor	\$17,200
	Materials and Consumables	\$18,000
	Utilities and Fuel	\$6,000
	Equipment Rentals	
	- 1 Conex boxes	\$2,200
	- Water Quality Meter	\$2,000
	Performance Testing/Analysis	\$92,200
	- Lab analysis	\$9,400
	- Testing after completion for one year on quarterly basis	
Sub-Total \$147,000		
TOTAL COSTS		
TOTAL TECHNOLOGY COST \$465,600		
Quantity Treated: 2,888 yd ³		
Unit Cost (\$): \$161/yd ³		

(a) Estimates based on pilot testing of 1 sparge well and three 2" PVC monitoring wells 120 ft deep with 1 ft. screened depth.

(b) Based on an area 130 ft by 30 ft by 20 ft with 5 sparge wells and 10 monitoring wells operated for a period of 2 years.

Table 9. CAS Sensitivity Analysis

<i>Number of Sparge Wells Decreases with Increased Sparge Radius of Influence</i>			
	15-ft radius of influence	25-ft radius of influence	Cost Impact
Sparge wells	\$14,880	\$8,930	(\$5,950)
Flash arrestors	\$2,500	\$1,500	(\$1,000)
Materials and consumables	\$16,000	\$12,000	(\$4,000)
Adjusted unit cost per cubic yard			\$157
<i>Installation Cost Decrease with Decreased Vadose Zone Thickness</i>			
	100 ft vadose zone	20 ft vadose zone	Cost Impact
Monitoring wells	\$29,760	\$9,920	(\$19,840)
Sparge wells	\$14,880	\$4,960	(\$9,920)
Labor	\$11,500	\$4,310	(\$7,190)
PID rental	\$900	\$340	(\$560)
Adjusted unit cost per cubic yard			\$148
<i>Monitoring Costs with Decreased Treatment Duration</i>			
	2 Years	1 Year	Cost Impact
Analytical testing	\$92,160	\$46,080	(\$46,080)
Labor	\$17,115	\$8,560	(\$8,555)
Electrical	\$5,760	\$2,880	(\$2,880)
Adjusted unit cost per cubic yard			\$141
<i>Monitoring Costs with Increased Treatment Duration</i>			
	2 Years	5 Years	Cost Impact
Analytical testing	\$92,160	\$168,960	\$76,800
Equipment maintenance	\$0	\$3,600	\$3,600
Labor	\$17,115	\$42,800	\$25,685
Electrical	\$5,760	\$14,400	\$8,640
Adjusted unit cost per cubic yard			\$201

5.3 Cost Comparison

Tables 10 and 11 show costs for a similar 30-ft by 20-ft by 130-ft by deep site using conventional air sparging with GAC to capture the sparged off-gas and using P&T, respectively.

Estimated CAS (\$161/cy) and conventional AS (\$163/cy) costs were very competitive at the selected scale for comparison, whereas P&T costs (\$313/cy) were much higher, as expected. Although the costs of CAS and conventional air sparging were similar for the scale selected for this cost comparison, the relative costs of CAS would likely decrease per unit treated volume, and the cost of conventional air sparging would be relatively linear. This is because CAS has upfront costs whose relative costs would decrease in proportion to the total project cost with increased scale. Such upfront costs include the microcosm studies (estimated at approximately \$50,000), pilot testing (estimated at approximately \$36,000), and groundwater and vadose zone monitoring, both of which could decrease significantly once the efficacy of the process at the site is confirmed.

Table 10. Estimated Full-Scale Implementation Costs for Conducting Air Sparging at McClellan AFB, California^(a)

Cost Category	Sub Category	Costs (\$)
FIXED COSTS		
CAPITAL COSTS	Mobilization/demobilization	\$50,000
	Planning/Preparation	\$40,000
	Investigation and Testing	\$37,700
	Equipment Cost	
	- GAC Canister	\$6,000
	- Oil-less Compressor	\$20,000
	Blower (20 hp)	\$2,600
	Start-up and Testing	\$41,300
	Other	
	- Installation	\$56,600
	- Engineering	\$20,000
	- Management Support	\$15,000
Sub-Total		\$289,100
VARIABLE COSTS		
OPERATION AND MAINTENANCE	Labor	\$12,700
	Materials and Consumables	\$90,000
	Utilities and Fuel	\$6,000
	Equipment Rentals	
	- Conex Box	\$2,200
	- Water Quality Meter	\$2,000
	Performance Testing/Analysis	
	- During sparging – water for VOCs	\$56,200
	- Air sampling	\$2,900
	- After completion VOCs	\$9,400
Sub-Total		\$181,000
TOTAL COSTS		
TOTAL TECHNOLOGY COST		\$470,100
Quantity Treated:		2,888 yd ³
Unit Cost (\$):		\$163/yd ³

(a) Based on an area 130 ft by 30 ft by 20 ft with 5 sparge wells and 10 monitoring wells operated for a period of 2 years.

Table 11. Estimated Full-Scale Implementation Costs for Pump and Treat at McClellan AFB, California^(a)

Cost Category	Sub Category	Costs (\$)
FIXED COSTS		
CAPITAL COSTS	Mobilization/demobilization	\$50,000
	Planning/Preparation	\$40,000
	Site Work	\$20,000
	Equipment Cost	
	- Pump	\$10,000
	- GAC Canister	\$60,000
	- Holding Tank	\$15,000
	Start-up and Testing	\$16,300
	Other	
	- Installation	\$45,400
	- Engineering	\$20,000
	- Management Support	\$15,000
Sub-Total		\$291,700
VARIABLE COSTS		
OPERATION AND MAINTENANCE	Labor	\$19,500
	Materials and Consumables	
	- GAC replacement	\$540,000
	- Other	\$15,000
	Utilities and Fuel	\$12,000
	Performance Testing/Analysis	
	- VOCs during pump and treat	\$30,500
	- After pump and treat completed	\$7,000
Sub-Total		\$613,100
TOTAL COSTS		
TOTAL TECHNOLOGY COST		\$904,800
Quantity Treated:		2,888 yd ³
Unit Cost (\$):		\$313/yd ³

(a) Based on an area 130 ft by 30 ft by 20 ft with 10 monitoring wells and one extraction well operated for a period of 10 years.

A geotechnical evaluation of the site is required to assess the efficacy of this technology compared to others. The geotechnical evaluation was not included in the cost estimate, because it was assumed that this would be performed during the remedial investigation phase of the site, and because virtually all in situ technologies would require a geotechnical analysis. No unique requirements for site preparation are foreseen, except to ensure that power and water are

available to the site. Some concern may be present if utilities have the potential to act as conduits for gas transport off site or to a building. Thus, some precautions may be required on a site specific basis to protect against such an occurrence. Similar precautions are required for air sparging, to ensure that contaminants do not enter buildings.

The technology is not sensitive to weather, although all equipment and the outdoor propane tank should be grounded properly. Fire protection is very important for the CAS process because of the on site use of propane, a flammable and explosive gas. However, propane (and to some extent methane) is well integrated into the U.S. infrastructure. Hence, regulatory guidelines for safe propane use should be followed, in addition to added protection against propane release into the atmosphere through off-gas venting or line leaks.

Treatment of residuals is often a part of most remediation projects. Residuals include drilling cuttings and water from groundwater sampling. Proper handling of residuals also will help protect workers against contaminant exposure, but also impacts costs for residuals disposal.

Permits may be required for underground propane injection. For McAFB, permits were not required.

6. Implementation Issues

6.1 Cost Observations

Key factors that affected project costs were depth to groundwater, the size of the plume, and operating and monitoring requirements. These factors would affect virtually any technology, specifically any sparging-related technology.

Depth to groundwater required drilling to over 110 ft bgs. For full-scale treatment, even deeper drilling would be required to extend the technology beneath the area of groundwater contamination. Depth to groundwater cannot easily be avoided and there are no factors that could be enhanced to eliminate this treatment obstacle. For this study, drilling cost approximately \$100,000 to drill sparge and monitoring points for the control and active test plots combined.

At McAFB, the size of the plume would significantly impact a sparging-related technology. With a radius of influence of approximately 15 ft, sparging requires frequent well placement to gain coverage within the plume. As the *Cost and Performance* report attests, at the OU A plume the 15-ft spacing resulted in several hundred sparge wells. The environmental engineering field increasingly finds that technologies benefit from relatively close well spacing, for optimal performance; close well spacing can improve such technologies as sparging, nutrient and electron donor injection, bioaugmentation, chemical injection, and bioslurping, for examples. The benefit of closer well spacing must be balanced against the increased cost for additional wells and operation and maintenance requirements incurred by reducing the spacing between wells. The 15-ft well spacing used for this study is a default design spacing recommended by the *Air Sparging Design Paradigm* (Leeson et al., 2001).

System operation and maintenance significantly impacted costs for this demonstration. However, enhanced maintenance and monitoring of groundwater and soil gas points were required due to the experimental nature of this demonstration. For a full-scale sparging or CAS site, efforts would be made to minimize the number of monitoring points, monitoring frequency, and to automate a sparge system to minimize the O&M time required in the field. The addition of propane adds a level of complexity, due to safety concerns, that makes reduction of O&M for CAS more difficult than conventional air sparging.

At most sites, a pilot demonstration of this technology would be necessary, before it is implemented at full scale. This study determined that prolonged exposure to propane for more than 500 days did not stimulate propane degraders in the vadose zone. Thus, it is likely that such pilot studies could be operated for a much shorter time period than used for this demonstration. This would significantly reduce demonstration costs. Furthermore, pilot studies should be conducted only if propane degradation and CAH cometabolism can be demonstrated for the saturated and vadose zones in laboratory microcosm studies before the field demonstrations.

For sites where sparging is already being applied, the addition of a propane injection system would be a much smaller incremental cost than for sites where no sparging is intended and all equipment would have to be purchased or leased for the CAS demonstration alone.

6.2 Performance Observations

CAS performance in the saturated zone met expectations and showed effective control of groundwater CAH concentrations. CAS was competitive with sparging only, and appeared to maintain lower concentrations than sparging alone, near or below groundwater MCLs. (It should be noted that the CAS sparging was conducted to minimize stripping into the vadose zone, and that sparging was not optimized to strip CAHs from the saturated zone.) Rapid propane degradation and subsequent CAH cometabolism were seen after a 40-day lag period, which matched laboratory microcosm results. These results indicate that the laboratory microcosms were good indicators of propane degradation, CAH cometabolism, and lag periods in the field.

Performance in the vadose zone did not meet expectations. After more than 500 days of exposure to propane in soil gas (approximately 1 to 4%), there was no evidence of propane degradation in the vadose zone and no evidence of CAH cometabolism. Attempts were made to stimulate methanotrophic CAH cometabolism by injecting methane into the vadose zone. These attempts were successful after a lag period.

The inability of the CAS process to stimulate cometabolic degradation CAHs in the vadose zone will decrease the cost competitiveness of the technology. The CAS process will still result in lower O&M costs due to more rapid CAH degradation, but a careful cost analysis must be conducted. Other sites may achieve cometabolic degradation in the vadose zone, because it is unknown why this did not occur at McAFB. It is probable and even likely that propane (or other growth substrate, depending on its selection) would degrade in the vadose zone and that this technology would be applicable to other sites.

6.3 Scale-Up

Scale up of CAS would be very similar to any sparging technology. Cost reductions would be realized by sharing equipment among sparge wells (i.e., compressors and propane injection), minimizing monitoring points and monitoring requirements, and minimizing the number of sparge points. Sparge points could be minimized by creating sparge curtains or barriers or by focusing only on hot spots, rather than trying to treat an entire aqueous plume. However, these savings would have to be balanced against other factors such as prolonged treatment and O&M requirements.

Any full-scale implementation of CAS would require first the demonstration of CAS in saturated and unsaturated soils using laboratory microcosms. This would be followed by the demonstration of CAS in the field using a simple, scaled down version of this demonstration. Cost reductions for the field demonstration would be seen by 1) eliminating the control test plot; 2) reducing the number of groundwater monitoring wells and vertical monitoring points; 3) reducing monitoring frequency; and 4) reducing the duration of the pilot test.

The size of a site will impact virtually any treatment technology. In the case with CAS, as with conventional air sparging, sparge wells have a limited radius of influence (generally approximately 15 ft is used as a rule of thumb, unless otherwise measured in the field). Increased sparge rates or sparge pressures cannot expand this limited radius of influence. Thus, in general, the number of sparge wells is directly proportional to the size of the site. CAS costs

can be minimized by strategically placing sparge wells to optimize their efficacy for either hot-spot removal or plume control.

The introduction of propane, methane, or butane gases with the sparged air stream introduces health and safety concerns and the need for additional security/safety measures. Safety considerations employed for this demonstration included 1) following all codes for propane use; 2) installing flash arrestors in all gas-transport lines; 3) sending the growth substrate gas and air to the saturated zone in separate lines, where they were mixed approximately 100 ft bgs in a 10-ft stainless steel sparge well; 4) pressure testing all propane (or methane) gas lines weekly to check for potential leaks; 5) using only hard pipe for propane lines; and 6) fencing the site to exclude unwelcome visitors. Other safety criteria may be required on a site-specific basis.

6.4 Lessons Learned

CAS was effective for treatment of groundwater but ineffective in the vadose zone, resulting in incomplete contaminant removal from the site. Based on work by others, such as at Dover AFB (Sayles, 2000), it is reasonable to conclude that CAS could effectively treat vadose zone contaminants at different sites. However, CAS should be demonstrated using microcosms of saturated and vadose zone soils before entering into the field effort.

In particular, users should be aware of the following:

- It is critical that propane degradation and CAH cometabolism be demonstrated in laboratory microcosms before initiating field work.
- Laboratory studies should be conducted using CAH concentrations similar to those observed in the field.
- Nutrient requirements should be assessed in the laboratory. Sites where nitrogen or other nutrient limitations persist may limit the efficacy of this process.

6.5 End-User Issues

The air sparging technology has been widely applied for many years at DoD installations and has already gained fairly widespread acceptance. The modification of the air sparging process to include a cometabolic growth substrate such as propane or butane remains promising, but may require more investigation. Additional work is required to evaluate conditions under which cometabolism can be stimulated in the vadose zone. Such studies can be conducted at a significantly reduced cost, compared to this study, by reducing the number of wells and monitoring points, eliminating the need for a control site, and simplifying the overall treatment process.

The introduction of propane, methane, or butane gases with the sparged air stream introduces health and safety concerns and the need for additional security/safety measures, as discussed in Section 6.3.

6.6 Approach to Regulatory Compliance and Acceptance

Air sparging is now well accepted by regulators and is routinely employed at a number of sites throughout the country. Permitting issues are often involved in the discussion of vapor capture and treatment. While air sparging systems can operate efficiently without vapor capture, SVE systems are often routinely installed in conjunction with air sparging systems. SVE systems are necessary if subsurface structures or buildings exist within the zone of influence of the air sparging system, or when chlorinated solvents that cannot easily be degraded in the vadose zone are sparged.

At sites where chlorinated solvents are present, the addition of cometabolic growth substrates could hypothetically stimulate biological processes in the saturated zone, thereby eliminating the need to capture and treat volatilized contaminants using an SVE process. The success of this process for both the saturated and vadose zones has yet to be fully demonstrated. The goal of this research effort was to demonstrate propane degradation and CAH cometabolism in both the saturated and vadose zones. Success was seen only in the saturated zone during the time allotted for this study. Potential success in the vadose zone occurred at the end of the study, when CAH compounds disappeared in the presence of methane degradation in the vadose zone; however these results could not be verified. Additional work is needed to demonstrate the efficacy of this technology for both saturated and vadose zones before regulatory acceptance can be expected. Concentrations in the saturated zone dropped below or approached MCLs for TCE and *c*-DCE, suggesting that this technology should prove acceptable to regulators once the additional work for vadose zone treatment is conducted.

7. References

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8. Points of Contact

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APPENDIX A

COST AND PERFORMANCE BACKUP

McClellan CAS Demonstration Costs

Cost Category		Sub Total	Costs
FIXED COSTS - CAPITAL COSTS			
Mobilization/Demobilization			\$15,992
Planning/Preparation			\$24,203
	Labor	\$24,063.86	
	Materials	\$139.15	
Site investigation and testing			\$40,408
	nutrient addition testing	\$16,500	
	microcosm study- field work	\$16,000	
	Drilling, analytical work	\$7,725.35	
	Materials	\$182.48	
Equipment Cost			
	Total Hydrocarbon Analyzer		\$16,000
	Oil-less air compressor		\$12,500
Start-up and Testing			\$10,000
Other			\$20,588
	Non-Process Equipment		
	Bladder pumps (28)	\$5,922.00	
	Well head for 2" wells (28)	\$2,812.95	
	Automatic pump control unit (2)	\$3,714.28	
	Riser for propane	\$737.15	
	Pressure Recorder	\$474.82	
	Propane	\$4,554.04	
	ground pumps	\$1,161.44	
	Other	\$1,211.55	
	Installation		\$29,909
	GC installation and repair	\$6,885.54	
	welder, gauge, hose	\$1,300.00	
	Other	\$21,723.64	
	Engineering		\$20,000
	Management Support		\$15,000
		Sub-total =	\$204,600

VARIABLE COSTS - OPERATION AND MAINTENANCE		
Labor	Field personnel - on-site	\$90,000
	Battelle personnel - on-site	\$25,000
	Travel	\$24,000
	OSU on-site lodging	\$16,000
Materials and Consumables		\$16,000
Utilities and Fuel		\$300
Equipment Rentals	Rental of 2 conax boxes	\$3,464.36
	Tank rentals	\$4,000.00
	Other rentals	\$3,400.00
	Rental of lowflow pump kit	\$190.25
	Rental of Aquastar data logger	\$263.99
	Pressure transducer rental	\$285.54
	Forklift rental	\$182.31
	Redi-Flo2 rental with controller	\$468.00
	200 ft water level meter rental	\$247.75
	Bladder pump controller rental	\$215.96
	Single pump kit with tube holder	\$315.00
	Quality meter rental	\$473.54
	other	\$757.66
Performance Testing/Analysis	Outside Laboratory	\$4,328.00
	Alpha Analytical	\$722.00
	Chester Labnet 5/24/00	\$2,475.00
	Air Toxics Ltd	\$1,131.00
	Battelle lab and data analyses	\$15,000
	Field GC work	\$19,001
	other	\$2,275
	data analysis software	\$743.43
	PID lamp model 108-10.0/10.6	\$608.16
	GS-Q Capillary columns (2)	\$923.20
Other direct costs		\$403
	Copying, printing & film	\$263.16
	Zip drive and disks	\$140.01
Oregon State University		\$264,000
McClellan Funding:		\$200,000
Subtotal:		\$687,171
Total Costs		
Total Technology Costs:		\$891,771
Quantity Treated (cubic yard):		523
Unit Cost per cubic yd:		\$1,705

Cometabolic Air Sparging for 2 years on a 130 X 30 X 20 plot

Cost Category		Sub Total	Costs
FIXED COSTS - CAPITAL COSTS			
Mobilization and demobilization:			\$50,000
Planning and Preparation:	work plan and HASP		\$40,000
Site Investigation:	Microcosm		\$50,000
	Pilot testing		\$36,499
	6-pk propane	\$1,300	
	3 monitoring wells, 120 ft deep @ \$24.80/ft. ^(a)	\$8,928	
	3 dedicated well heads	\$285	
	3 bladder pumps	\$635	
	3 Soil gas tubing	\$101	
	1 sparge well, 120 ft deep @ 24.80/ft. ^(a)	\$2,976	
	1 flash arrestor	\$500	
	1 Automatic pump controller	\$1,700	
	1 DO meter	\$515	
	labor	\$19,560	
Equipment Cost:	1 Oil-free 30 hp 100 psi air compressor		\$20,000
	Hydrocarbon Analyzer		\$16,000
Start-up and Testing:			\$17,000
	Analytical testing: Vocs and Inorganics	\$15,360	
	Training: 40-hr Hazwoper	\$1,640	
Other:	Propane Tank		\$5,004
	propane	\$4,554	
	delivery charge and tank rental	\$450	
	Installation		\$49,517
	4 sparge wells, 120 ft deep @ 24.80/ft. ^(a)	\$11,904	
	4 flash arrestors	\$2,000	
	7 monitoring wells, 120 ft deep @ \$24.80/ft. ^(a)	\$20,832	
	7 dedicated well heads	\$665	
	7 bladder pumps	\$1,481	
	7 soil gas tubing	\$235	
	1 Geoloaist/Engineer (full-time for 4 weeks) ^(a,b)	\$4,980	
	2 Technicians (full-time for 4 weeks) ^(a,c)	\$6,520	
	1 PIDs (weekly rental for 4 weeks) ^(a)	\$900	
	Engineering		\$20,000
	Management Support		\$15,000
Sub-total:			\$319,020

VARIABLE COSTS - OPERATION AND MAINTENANCE		
Labor:	technician 8hrs/week for two years	\$17,115
Miscellaneous Material and Consumables^(d)		\$18,000
Utilities and Fuel	electrical ^(a,e)	\$5,760
Equipment Rentals		\$4,200
	horiba for water quality parameters	\$2,000
	Conex Box	\$2,200
Performance Testing/Analysis		\$101,520
	Analytical - VOCs and Inorganics for once a week for first two months, then once a months for rest of two years	\$92,160
	Analytical after sparging completed for 1 year with quarterly samples for VOCs only	\$9,360
	Sub-total:	\$146,595
Total Costs		
	Total Technology Costs:	\$465,615
	Quantity Treated (cubic yard):	2,888
	Unit Cost per cubic yd:	\$161

(a) "Environmental Remediation Cost Data- Unit Price." Fifth Edition. RS Means. (1999)

(b) \$31.31/hour

(c) \$20.38/hour

(d) Includes plumbing, hardware, tubing, sampling containers and other consumable items. Estimate is based on cost of consumables during the pilot field study at McAFB.

(e) \$240/month for miscellaneous electrical site usage

Air Sparging for 2 years on a 130 X 30 X 20 plot

Cost Category		Sub Total	Costs
FIXED COSTS - CAPITAL COSTS			
Mob/demob:			\$50,000
planning/prep:	work plan and HASP		\$40,000
Site investigation and testing:			
	Pilot testing		\$37,675
	3 monitoring wells, 120 ft deep @ \$24.80/ft. ^(a)	\$8,928	
	3 dedicated well heads	\$285	
	3 bladder pumps	\$635	
	3 Soil gas tubing	\$101	
	1 sparge well, 120 ft deep @ 24.80/ft. ^(a)	\$2,976	
	1 SVE well	\$2,976	
	1 Automatic pump controller	\$1,700	
	1 DO meter	\$515	
	labor	\$19,560	
Equipment			
	GAC canisters		\$6,000
	Oil-free 30 hp 100 psi air compressor		\$20,000
	Blower (20 hp)		\$2,600
Start-up and Testing			
	pump test	\$15,000	
	helium test	\$25,000	
	Training: 40-hr Hazwoper	\$1,281	
Other			
	Installation		\$56,568
	4 sparge wells, 120 ft deep @ 24.80/ft. ^(a)	\$11,904	
	2 SVE well	\$5,952	
	7 monitoring wells, 120 ft deep @ \$24.80/ft. ^(a)	\$20,832	
	7 dedicated well heads	\$665	
	7 bladder pumps	\$1,481	
	7 soil gas tubing	\$235	
	1 Geologist/Engineer (full-time for 5 weeks) ^(a,b)	\$6,225	
	2 Technicians (full-time for 5 weeks) ^(a,c)	\$8,150	
	1 PIDs (weekly rental for 5 weeks) ^(a)	\$1,125	
	Engineering		\$20,000
	Management Support		\$15,000
Total Cost:			\$289,125

VARIABLE COSTS - OPERATION AND MAINTENANCE		
Labor:	technician 6hrs/week for two years	\$12,714
Miscellaneous Material and Consumables		\$90,000
	Replacement GAC ^(d)	\$72,000
	other ^(e)	\$18,000
Utilities and Fuel	electrical ^(a,f)	\$5,760
Equipment Rentals		\$4,200
	horiba for water quality parameters	\$2,000
	Conex Box	\$2,200
Performance Testing/Analysis		\$68,340
	Analytical - VOCs for once a month for two years	\$56,160
	Air Sampling - VOCs every other month	\$2,820
	Analytical after sparging completed for 1 year with quarterly samples for VOCs only	\$9,360
		Sub-total: \$181,014
Total Costs		
		Total Technology Costs: \$470,139
		Quantity Treated (cubic yard): 2,888
		Unit Cost per cubic yard: \$163

(a) "Environmental Remediation Cost Data- Unit Price." Fifth Edition. RS Means. (1999)

(b) \$31.31/hour

(c) \$20.38/hour

(d) \$6000 per GAC canister. one canister required for two months.

(e) Includes plumbing, hardware, tubing, sampling containers and other consumable items. Estimate is based on cost of consumables during the pilot field study at McAFB.

(f) \$240/month for miscellaneous electrical site usage

Pump and Treat for 10 years on a 130 X 30 X 20 plot

Cost Category		Sub Total	Costs
FIXED COSTS - CAPITAL COSTS			
Mob/demob:			\$50,000
planning/prep:	work plan and HASP		\$40,000
Site investigation and testing:			\$20,000
Equipment			\$85,000
	1 GAC canister ^(a)	\$60,000	
	1 pump	\$10,000	
	1 holding tank	\$15,000	
Start-up and Testing			\$16,281
	pump test	\$15,000	
	Training: 40-hr Hazwoper	\$1,281	
Other	Installation		\$45,436
	1 extraction well. 120 ft deep @ 24.80/ft. ^(b)	\$2,976	
	10 monitoring wells. 120 ft deep @ \$24.80/ft. ^(b)	\$29,760	
	10 dedicated well heads	\$950	
	10 bladder pumps	\$2,115	
	10 soil gas tubing	\$335	
	1 Geologists (full-time for 3 weeks) ^(b,c)	\$3,735	
	2 Technicians (full-time for 3 weeks) ^(b,d)	\$4,890	
	1 PIDs (weekly rental for 3 weeks) ^(b)	\$675	
	Engineering		\$20,000
	Management Support		\$15,000
	Sub Total:		\$291,717
VARIABLE COSTS - OPERATION AND MAINTENANCE			
Labor:	1 technician 8hrs/month for ten years ^(b,d)		\$19,500
Miscellaneous Material and Consumables ^(e)			\$15,000
	GAC replacement \$60,000/yr for 9 years ^(a)		\$540,000
Utilities and Fuel	electrical ^(f)		\$1,176
Performance Testing/Analysis			\$37,440
	Analytical - VOCs for once a quarter for the first year, then once a year for the next 9 years	\$30,420	
	Analytical after sparging completed for 1 year with quarterly samples for VOCs only	\$7,020	
	Sub Total:		\$613,116
Total Costs			
	Total Technology Costs:		\$904,833
	Quantity Treated (cubic yard):		2,888
	Unit Cost per cubic yard:		\$313

(a) \$60000 per GAC canister. one canister required for water treatment per twelve months.

(b) "Environmental Remediation Cost Data- Unit Price." Fifth Edition. RS Means. (1999)

(c) \$31.31/hour

(d) \$20.38/hour

(e) Includes plumbing, hardware, tubing, sampling containers and other consumable items. Estimate is based on cost of consumables during the pilot field study at McAFB.

(f) \$240/month for miscellaneous electrical site usage

Cometabolic Air Sparging Analytical Table					
Time	Analysis	Number of Samples	Frequency	Cost per sample	Total cost
Baseline	VOCs -groundwater	12 monitoring wells	once a week for two months	\$195	\$18,720
	Inorganics (nitrate) - groundwater	12 monitoring wells	once a week for two months	\$61	\$5,856
In-progress	VOCs -groundwater	12 monitoring wells	once a month for rest of two years	\$195	\$51,480
	Inorganics (nitrate) - groundwater	12 monitoring wells	once a month for rest of two years	\$61	\$16,104
After completeion	VOCs -groundwater	12 monitoring wells	once per quarter for one year	\$195	\$9,360
Total =					\$101,520

Samples will be taken once a week for the first two months then once per month for the rest of the two year period.

After completion of project, samples will be collected once a quarter for one year.

Air Sparging Analytical Table					
Time	Analysis	Number of Samples	Frequency	Cost per sample	Total cost
In-progress	VOCs -groundwater	12 monitoring wells	once a month for two years	\$195	\$56,160
	VOCs - off gas	1 off-gas point	every other month for two years	\$235	\$2,820
After completeion	VOCs -groundwater	12 monitoring wells	once per quarter for one year	\$195	\$9,360
Total =					\$68,340

Samples will be taken once a month for the two year period for groundwater. Off-gas will be collected every other month for the two years.

After completion of project, samples will be collected once a quarter for one year.

Pump and Treat Analytical Table					
Time	Analysis	Number of Samples	Frequency	Cost per sample	Total cost
Baseline	VOCs -groundwater	9 monitoring wells & 3 GAC effluent ports	once a quarter for first year	\$195	\$9,360
In-progress	VOCs -groundwater	9 monitoring wells & 3 GAC effluent ports	once a year for next 9 years	\$195	\$21,060
After completeion	VOCs -groundwater	9 monitoring wells	once per quarter for one year	\$195	\$7,020
Total =					\$28,080

Samples will be taken once a quarter for first year, then once a year for the next 9 years.

After completion of project, samples will be collected once a quarter for one year.

CAS SENSITIVITY ANALYSIS

Number of sparge wells decreases with increased radius of influence

15 ft radius of influence

	Number	Cost
Sparge wells	5	\$14,880
Flash Arrestors	5	\$2,500

25 ft radius of influence

	Number	Cost
Sparge wells	3	\$8,928
Flash Arrestors	3	\$1,500

Installation costs decrease with decreasing vadose zone thickness

100 ft deep vadose zone

	Number	Cost
Monitoring wells, 120 ft deep @ 24.80/ft.	10	\$29,760
Sparge wells, 120 ft deep @ 24.80/ft	5	\$14,880
Labor	4 weeks	\$11,500
PID rental	4 weeks	\$900

20 ft deep vadose zone

	Number	Cost
Monitoring wells, 40 ft deep @ 24.80/ft.	10	\$9,920
Sparge wells, 40 ft deep @ 24.80/ft	5	\$4,960
Labor	1.5 weeks	\$4,313
PID rental	1.5 weeks	\$338

Costs increase with increasing test duration

1 year

	Cost
Analytical testing: VOCs and Inorganics once a week for 2 months then once a month for the rest of one year	\$46,080
Equipment maintenance	\$0
Labor (technician 8 hrs/week for 1 year)	\$8,558
Electrical	\$2,880

5 years

	Cost
Analytical testing: VOCs and Inorganics once a week for 2 months then once a month for the rest of five years	\$168,960
Equipment maintenance	\$3,600
Labor (technician 8 hrs/week for 5 years)	\$42,788
Electrical	\$14,400